Thermoplastic composite sandwiches for structural helicopter applications

Von der Fakultät für Ingenieurwissenschaften
der Universität Bayreuth
zur Erlangung der Würde eines
Doktor-Ingenieurs (Dr.-Ing.)
genehmigte Dissertation

von
Dipl. Ing. Jonas Grünewald
aus
Köln

Erstgutachter: Professor Dr.-Ing. Volker Altstädt
Zweitgutachter: Professor Dr.-Ing. Alois K. Schlarb
Tag der mündlichen Prüfung: 08.02.2018

Lehrstuhl für Polymere Werkstoffe
Universität Bayreuth
2018

Short summary

Composite sandwich structures offer excellent lightweight properties for the aviation industry. Replacing thermoset based materials and honeycomb structures with thermoplastic composite (TPC) materials and foam cores seems promising for lowering manufacturing and in-service costs and thereby the direct operating costs of aviation vehicles.

Consequently, this thesis deals with the development of sandwich structures based on carbon fibre (CF) reinforced Polyetheretherketone (PEEK) skins and Polyetherimide (PEI) foam cores for structural sandwich applications in helicopters. Skins and core are joined cohesively by fusion bonding, a technique which leads to high bond strengths while being realisable in short cycle times. However, CF/PEEK skins and PEI foam cannot be readily joined due to their incompatible processing requirements, therefore the 'Thermabond' principle, which is based on enriching thermoplastic composite laminates with a second polymer to simplify the fusion bonding process, is adapted to the sandwich manufacturing process. To understand the process governing mechanisms, and to define a process window which enables high bond strengths while preventing skin de-consolidation and core collapse, a theoretical model based on 'intimate contact' and 'healing' is deduced for the manufacturing process. This model enables the prediction of the skin-to-core bond depending on varying skin and core temperatures. In the following, experimental trials are conducted according to the parameters resulting from the model for verification. The comparison shows a reasonably good agreement between predicted and experimentally obtained skin-to-core bond strengths with skin temperatures in the range of 290 °C – 320 °C. However, while the model predicts that core heating leads to an improvement of the bond strength, experiments show that core heating often leads to core collapse, which is not considered in the model. Therefore, it is proposed that the modelling approach is complemented with an analysis of the heat flow into core. Based on the defined skin temperatures and further process parameters, such as core compaction distance and PEI film thickness, a complementary characterisation of the sandwich structures is performed. The sandwich structures are tested according to several testing standards to characterise the skin-to-core bond, the core structure as well as the sandwich as a whole. The characterisation reveals that the proposed process parameters enable a strong fusion bond. Nevertheless, temperature and core compaction distance are observed to influence the core cell structure, which often leads to a weakening of the core performance. Based on the characterisation, it is proposed to manufacture the sandwich structures at a skin temperature of 300 °C, a compaction distance of 2 mm and to enrich the CF/PEEK skins with a 125 µm thick PEI film. Subsequently, the developed sandwich structures are compared to thermoset based state-of-the-art sandwich structures, namely prepreg-Nomex® (® = registered trademark) and Polymethacrylimide (PMI) foam based structures, and defined requirements. In general, the assessment shows lesser performance of the developed TPC sandwich structures, though reveals promising short manufacturing cycle times which can be half that of cycle times for state-of the-art aviation sandwiches. To improve the performance and be able to fulfil the requirements, concepts based on pin integration into the foam core are proposed and the potential of strengthening the core is illustrated. Finally, a formed panel is realised to show the performance of thermoplastic sandwich structures for formed parts. Thereby, it is shown that skins and core need to be formed prior to the fusion bonding process.

Kurzfassung

Faserverstärkte Sandwichstrukturen bieten großes Leichtbaupotential für die Luftfahrt. Der Austausch duroplastischer Materialien durch faserverstärkte thermoplastische Materialien, sowie der Ersatz von Nomex®-Waben (® = registered trademark) durch Schaumkern-strukturen ist vielversprechend für die Senkung der Herstellungs- sowie Wartungskosten von Luftfahrzeugen.

Aus diesem Grund beschäftigt sich diese Arbeit mit der Entwicklung von luftfahrttauglichen Sandwichstrukturen aus karbonfaserverstärkten (CF) Polyetheretherketon (PEEK) Deckhäuten und einem Polyetherimid (PEI) Schaumkern sowie deren Herstellungsprozess. Ziel dabei ist es, die Deckhäute und den Schaumkern über eine Schmelzverbindung, welche hohe Verbindungsfestigkeiten in kurzen Zykluszeiten ermöglicht, zu fügen. Vorversuche zeigen jedoch, dass sich die CF/PEEK-Deckhäute und der PEI-Schaumkern aufgrund ihrer divergierenden Verarbeitungsfenster im Hinblick auf Temperatur und Druck nicht ohne Weiteres über eine Schmelzverbindung fügen lassen. Aus diesem Grund wird der Herstellprozess an den “Thermabond“-Prozess, welcher auf der Anreicherung einer Deckhaut-Seite mit einem zweiten Polymersystem (in diesem Fall mit einer PEI-Schicht) basiert, angepasst und ein konvergentes Prozessfenster geschaffen. Um Verständnis für die Prozess-dominierenden Mechanismen zu gewinnen sowie ein geeignetes Prozessfenster zu identifizieren, wird ein theoretisches Modell für den Herstellprozess abgeleitet. Dieses Modell ermöglicht die Vorhersage der Deckhaut-Kern-Verbindungsfestigkeit in Abhängigkeit von verschiedenen Deckhaut- und Kerntemperaturen. Experimentelle Untersuchungen verifizieren in den meisten Fällen die vorhergesagten Verbindungsfestigkeiten und zeigen, dass Deckhauttemperaturen im Bereich von 290 °C bis 320 °C zu den erwünschten Verbindungsfestigkeiten führen. Jedoch zeigen die Experimente, dass neben der Verbindungfestigkeit auch die Formstabilität des Kernes betrachten werden muss, da es im Falle von erhöhten Kerntemperaturen zu einem Kollabieren des Kernes und somit zu Abweichungen zu den vorhergesagten Festigkeiten kommt. In einer ergänzenden Studie wird der Einfluss der Deckhauttemperatur, des Kernkompaktierungswegs und der Dicke der PEI-Oberflächenschicht auf die Verbindungsfestigkeit, die Kernstruktur sowie auf die gesamte Sandwichstruktur tiefergehend untersucht. Die Ergebnisse der ergänzenden Studie untermauern die hohen Deckhaut-Kern-Verbindungsfestigkeiten der Sandwichstrukturen, zeigen jedoch, dass bei erhöhten Deckhautemperaturen und hohen Kernkompaktierungswegen die Kernstruktur im Randbereich beeinflusst und somit die Kernstruktur geschwächt wird. Resultierend aus den Untersuchungen wird eine Deckhauttemperatur von 300 °C, 2 mm Kernkompaktierungsweg und 125 µm PEI-Deckhautbeschichtung für die Herstellung empfohlen. Die experimentell nachgewiesenen Eigenschaften im Vergleich mit duroplastischen Referenz-Sandwichstrukturen verdeutlichen das Potential der thermoplastischen Sandwichstrukturen im Hinblick auf die hohen Verbindungsfestigkeiten und die wesentlich kürzeren Herstellungszykluszeiten, heben jedoch auch den PEI-Schaumkern als Schwachstelle der Strukturen hervor. Daraufhin wird eine Methode zur Verstärkung der Schaumkerne vorgestellt, welche es ermöglicht, die Kerneigenschaften bzw. die Eigenschaften der gesamten Sandwichstruktur zu verbessern.

Im letzten Kapitel wird die Prozesstauglichkeit der thermoplastischen Sandwichstrukturen am Beispiel eines geformten, dreidimensionalen Schubpaneels nachgewiesen.

Acknowledgements

Firstly, I would like to express my sincere gratitude to my advisor Professor Dr.-Ing. Volker Altstädt for the continuous support of my study and research, as well as the possibility to investigate the field of thermoplastic sandwich structures in the framework of a PhD thesis. I would also like to thank Professor Dr. Ing. Alois Schlarb for his feedback and input and for the acceptance to be second assessor of this thesis.

A special thanks goes to Dr. Patricia Parlevliet, who supervised, accompanied and monitored each step of my work over the last few years. Thanks to her fundamental knowledge of thermoplastic materials and her experiences in scientific approaches and labour, she guided me through my studies and this thesis, but gave me enough freedom to create and develop my own ideas for my investigations. Furthermore, she always had a sympathetic ear and a lot of understanding for challenges and problems during my work, and always found the right words to keep me motivated.

Furthermore, I would like to thank all my colleagues from the department of composite technologies at Airbus Group Innovation for their support. I would especially like to thank Jürgen Filsinger for his technical expertise of thermoset based sandwiches and Florian Dorn, who helped me to find diplomatic solutions in disagreements. Moreover, I would like to thank Dr. Uwe Beier from Airbus Helicopters for his technical input and support during the project, as well as for his efforts in enabling me to realise this thesis.

In addition, I would like to thank the students, who helped me to conduct many experimental trials, which were an important contribution to my thesis. In particular, many thanks to Nicolas Baran, Nicolas Courtois, Julia Weimer, Vincent Backmann but especially to Alexander Matschinski who supported me for more than one year with inexhaustible passion and energy.

Moreover, I would like to thank my friend Darin McQuoid and Ralph Reindler from the University of Bayreuth for proof reading this thesis.

The thesis is performed partly in the framework of the project „MAI Sandwich - Entwicklung von thermoplastisch fügbaren Sandwichstrukturen unter Berücksichtigung eines sortenreinen und wiederverwertbaren Werkstoffeinsatzes“, No. 03MAI32A, which is funded by the German Federal Ministry of Education and Research via the M A I Carbon Cluster. Hence, I would also like to thank the Federal Ministry of Education and Research for funding research in the field of thermoplastic composite sandwiches.

Finally, I would like to thank the people figuring in my personal background. First and foremost, I would like to thank my mother so much for her unfailing love and backing in everything I do and dream about in life, in particular the opportunity to study and prepare this thesis. In addition, I would like to mention Christoph Meier and Tilman Orth, who became close friends during my time at Airbus Group Innovations. Thank you so much for the joy and enduring the suffering we experienced together.

Dedication

I would like to dedicate this thesis to my father, who is unfortunately not able to witness the finalisation of this thesis. Rest in peace!

Table of contents

Abbreviations

Adh	Adhesive
B.l. Coh	Boundary layer cohesive
CF	Carbon fibre
Coh	Cohesive
DCM	Dichloremethane
DOC	Direct Operating Costs
DCS	Differential scanning calorimetry
EPP	Expanded Polypropylene
FIM	Foam injection moulding
FST	Fire Smoke Toxicity
FVC	Fibre volume content
GF	Glass fibre
GMT	Glass fibre mat
ILSS	Interlaminar shear strength
IMC	Injection moulding compounding
IR	Infrared
LCC	Life cost cycle
MC	Methylene Chloride
MEK	Methyelthylketone
PA	Polyamide
PAEK	Polyaryletherketon
PBT	Polybutyleneterephthalate
PEEK	Polyetheretherketone
PEI	Polyetherimide
PES	Polyethersulfone
PET	Polyethylenterephthalate
PH	Prepreg-Honeycomb Sandwiches
PI	Polyimide
PMI	Polymethacrylimide
PP	Polypropylene
PPS	Polyphenylensulfid
Prepreg	Pre-impregnated
PTFE	Polytetrafluorethylene
®	Registred Trademark
RTM	Resin moulding transfer
RTM63	Sandwiches manufactured by RTM process with a PMI core (63 kg/m³)
TPC	Thermoplastic Composite
™	Unregistered trademark
UD	Unidirectional
UV	Ultraviolet
VAP	Vacuum assisted process
1D,2D,3D	One-dimensional, Two-dimensional, Three-dimensional

Formular symbols

a_0	Initial height of the rectangular elements (ideal material surface)
$a(t)$	Height after the time t of deformation (ideal material surface)
b_0	Width of the initial rectangular elements (ideal material surface)
$b(t)$	Width after the time t of deformation (ideal material surface)
C_{flt}	Cost for crew, fuel, insurance
C_{maint}	Cost for maintenance, repair, overhaul
C_{depr}	Cost for price, flight hours
C_{lnr}	Cost for landing and navigations fees, registry taxes
C_{fin}	Cost for financing strategy
c	Specific heat capacity
$d_{compaction}$	Core compaction distance
$dh_{(P,T,S,C)}$	Node distance for the elements of press, transfer plate, skin and core
D_h	Degree of healing
D_{ic}	Degree intimate contact
Δt	Time interval
Δx	Distance between node in x-direction
Δy	Distance between nodes in y -direction
δ_D	Dispersion cohesion (solubility) parameter
δ_H	Hydrogen bonding cohesion (solubility) parameter
δ_P	Polar cohesion (solubility) parameter
G_c	Fracture energy
$G_{c\infty}$	Fracture energy off a fully healed interface
$h_{(P,T,S,C)}$	Height of press, transfer plate, skin and core
I	Polymer chain end that exits the tube
L	Length of the fictitious tube
λ	Thermal conductivity
m,n	Node label
η	Polymer viscosity
p_{app}	Applied pressure
p	Pressure
Φ''	Heat generation
q	Amount of time intervals
Ro	Radius of interaction sphere in Hansen space
Ra	Distance in Hansen space
Red	RED number
ρ	Density
S	Sandwich thickness
S_{aimed}	Aimed sandwich thickness
t_p	Process time
σ	Fracture stress
σ_∞	Fracture stress of a fully healed interface
$\bar{\sigma}_{Tensile}$	Normalised Tensile strength
T_{core}	Core temperature

T_g	Glass transition temperature
T_m	Melting temperature
$T_{m,n}^{i+1}$	Temperature for the time point i+1 for node m,n
T_p	Processing temperature
T_r	Reptation time
Tr	Room temperature
T_{Skin}	Skin temperature (in contact with core)
$T_{Skin\ pre\text{-}heat}$	Skin pre-heat temperature (skin temperature in oven)
$T_{Transfer\ plate}$	Temperature of transfer plate in oven
τ	Shear stress
w_0	Initial width between the rectangular elements (ideal material surface)
$w(t)$	Width between the rectangular elements after time t (material surface)
χ	Average interpenetration distance
$\dot{\gamma}$	Shear velocity

Units

g	Gramm
hrs	Hours
J	Joule
kN	Kilo Newton
kg	Kilogramm
m	Metre
m²	Square meter
m³	Cubic meter
mm	Millimetre
µm	Micrometre
min	Minutes
MPa	Mega Pascal
N	Newton
sec	Seconds

1. INTRODUCTION AND MOTIVATION

Flying like birds, swimming like fish and constructing like insects: desires which have driven humans since the cradle of humankind to adapt natural phenomena into technology. One of the best-known examples is the myth of Daedalus and Icarus, who constructed wings based on the model of birds to escape from the tyrant Minus. Today, a scientific discipline in itself, referred to as bionics, engages with the adaptation of natural models into innovations.

The concept of sandwich structures is also based on natural principles [1]. Good examples are tree branches and bones in skeletons (Figure 1), both striving for the minimum use of material while obtaining maximum performance [1].

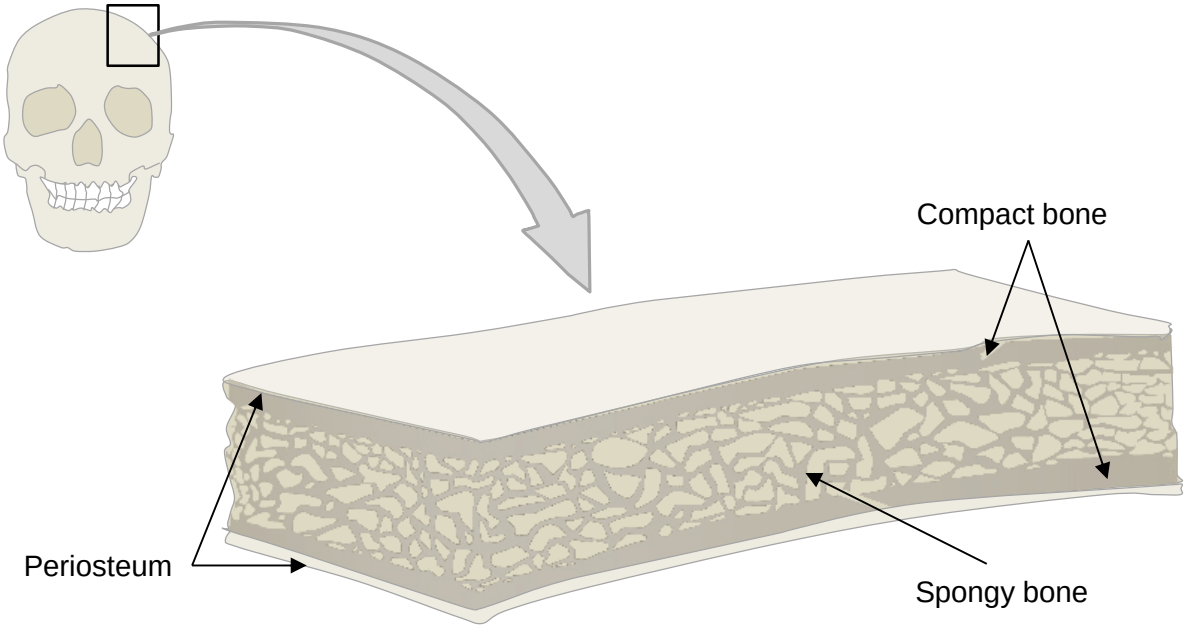
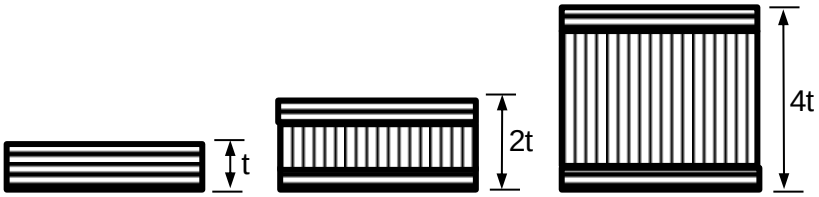


Figure 1: Cross-section of a flat bone shows the spongy bone lined on either side by a layer of compact bone [2]

Today, in engineering science, a sandwich is defined as a structure consisting of a relative thick, low density core material covered by relative thin skin materials [3]. Skins and core are force-fitted joined, in most cases by means of an adhesive capable of transmitting shear and axial loads from and to the core [4]. Under load, the skins bear tensile and compressive forces and are meant to protect the core against impacts [3]. The core separates the skins to the designated distance, while carrying compression and shear loads. This sandwich principle is comparable to the I-Beam concept [5]. Additionally, the core is supposed to stabilise the skins and support them against buckling and kinking [3]. Separating the skins by means of the core increases the mass moment of inertia of the panel while adding only little weight [4]. Thus, a structure is created which features a high resistance to bending and buckling. However, a strong bond between skins and core, more specifically a bond which is not the weakest link within the structure, is required to allow the sandwich principle to function [6]. By using typical values for skin and core density, the flexural stiffness and strength-to-weight ratio can be significantly improved compared to a monolithic panel, see Table 1. Further advantages of sandwich structures are acoustic and thermal insulation [1].

Table 1: Structural efficiency of sandwich panels in terms of weight in comparison to monolithic structures according to Petras [4]

			
Relative bending stiffness	1	7.00	37.00
Relative bending strength	1	3.50	9.20
Relative weight	1	1.03	1.06

Common materials for skins are aluminium, steel and wood, or composite materials for high performance applications, reinforced either by glass- or carbon fibres [4,5]. Core materials can be divided into two categories: isotropic and anisotropic core materials [3]. Materials such as cork or in some cases foams feature directional-independent properties (isotropic materials), while balsa wood, honeycomb and oriented foam cores show directional dependent features (anisotropic materials) [3,5].

The first description of the sandwich construction principle, consisting of iron sheets riveted to a wood core, was awarded to W. Fairbairn back in 1849 in England [7,8]. Since one of the major challenges in aircraft design is to decrease weight without sacrificing strength, engineers introduced the sandwich design into the aviation industry a long time ago [1]. Already in 1924 sandwich structures were first applied in aviation as a fuselage structure for a glider plane, followed by sandwich elements in wing structures [8,9]. In the thirties sandwich structures were used in powered aircraft such as the Comet Racer, the Albatross or the famous De Havilland Mosquito, which was regarded as one of the fastest operational aircraft in World War II [8]. For these aircraft sandwich structures, wood skins were combined with a balsa core and joined by the use of an adhesive based on phenolic resin [1,8,10]. In the late 1940's the concept for modern honeycombs was invented by a circus proprietor [11]. Metal-wood based sandwich panels were used in the Fokker F27 in 1955 [1,8]. In the early 60's the first sandwich rotor blades were designed for the BO 105, consisting of composite skins and foam in order to prevent local buckling of the skins [12]. By landing on the moon, the Apollo project showed the great potential of sandwich structures for aerospace engineering in 1969 [13]. Airbus began to make use of composite sandwiches structures in 1983, when the first Airbus aircraft was equipped with a composite honeycomb rudder [1].

With an increasing wealth of the world's population, the demand for personal mobility and especially for air travel has increased over the last few decades [14], leading to over 6 trillion revenue passenger kilometres in 2015 according to the International Civil Aviation Organization [15]. In order to satisfy the increasing demand of air traffic, but to stay profitable, aircraft manufacturers and airlines have been forced to drive the development of more-fuel efficient aircraft to minimise the direct operating costs (DOC) such as increasing fuel costs [16]. As a result, lightweight design has stepped more and more into the focus. Metallic parts have been partly replaced by composites and sandwich structures used in a variety of aviation applications. In today's aircraft, the typical structural sandwich elements are aerodynamic

fairings, covers and doors [1,17]. Some examples are radomes, belly fairings, leading and trailing edge fairings, engine cowlings and landing gear doors. Meanwhile applications in aircraft interiors such as fairings and floor panels have also become standard [18]. Since the whole weight of a helicopter has to be lifted by its rotating engines, lightweight design plays an even more important role for helicopters [19]. Up to 85 % of the structure is realised in composite materials today, such as in the Airbus NH90 helicopter [20]. Additionally, sandwich structures can be found in floor panels, cowlings, beams and frames, and rotor blades to further lower the weight, see Figure 2 [21].

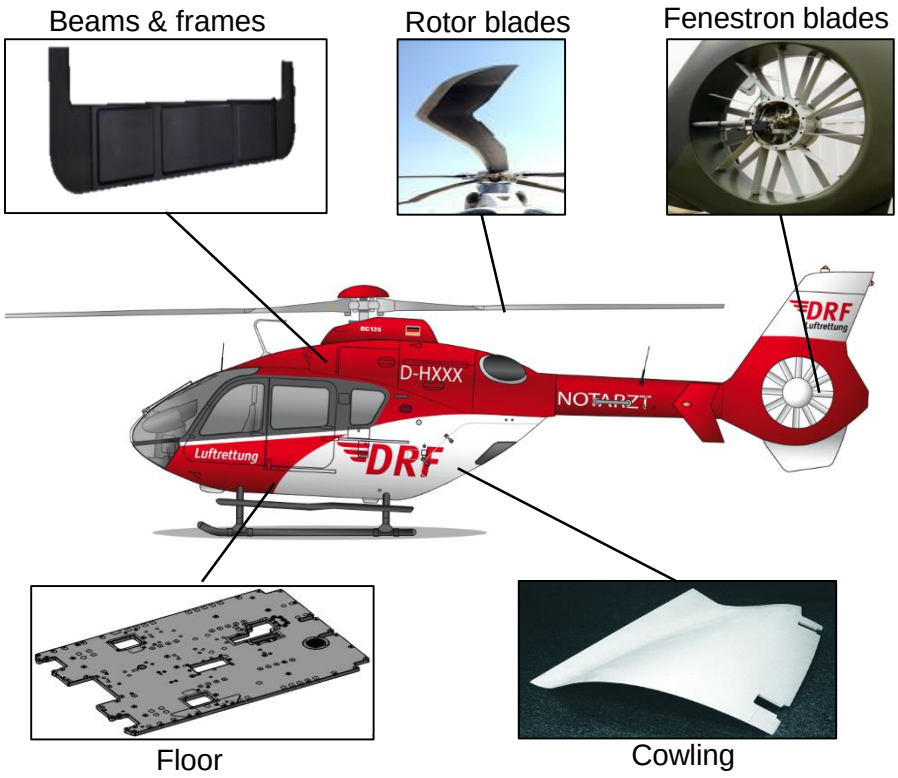


Figure 2: Typical applications for sandwich structures in helicopters

Today, the predominant skin material in aircraft and helicopter construction are glass- or carbon fibre reinforced prepregs (pre-impregnated) with epoxy or phenolic resins [1]. As core material, mostly honeycombs consisting of aramid paper impregnated with a phenolic resin are used [1,5]. Aramid/Phenolic honeycomb cores feature excellent stiffness and strength characteristics and have positive FST (Fire, Smoke & Toxicity) properties for interior applications [18]. It is considered highly doubtful that other sandwich structures can compete with honeycomb based structures regarding the weight-performance ratio, as shown in Figure 3.

However, despite their excellent performance and the wide background of knowledge on handling and design, honeycomb core structures have various drawbacks. Prepreg/honeycomb sandwich structures are costly, due to raw material prices [5], time and cost intensive production and required high machine investments [22]. Figure 4 gives an overview of the drawbacks of Prepreg/honeycomb based sandwiches in terms of manufacturing costs and impact on the environment during the whole life cycle. The production

of honeycomb core sandwiches is cost prohibitive due to time intensive processing which requires manual labour [23].

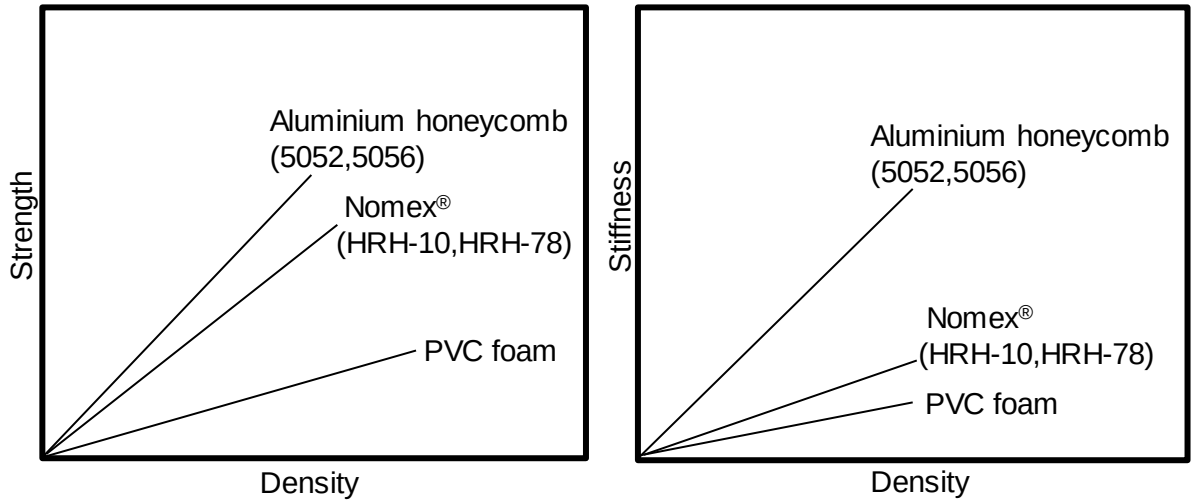


Figure 3: Strength and stiffness of various core materials according to Campbell [5]

Already the first production step, the forming of the core, is labour intensive. Since honeycombs are hard to form into complex parts, they have to be shaped or machined individually [18]. Due to the hexagonal and open structure, honeycombs require filling, potting and sealing [21]. Additionally, honeycomb cores tend to crush when subjected to lateral forces during processing, leading to the need of stabilisation [24].

After preparing and draping the prepreg stacks and adhesive layers, a vacuum-bag-setup has to be installed by manual labour, followed by consolidation and curing at elevated temperature and pressure in an autoclave [23]. Layup and vacuum bagging can be performed in a few hours, while autoclave consolidation takes up to a full day [23]. In addition, honeycomb sandwiches often require time-consuming post processing stages. Surface recesses, referred to as telegraphing, can be caused by the hexagonal structure of the honeycomb cores leading to the need of additional processing of the skins [18]. During service, honeycomb structures require costly and frequent maintenance since the honeycomb may fill up with water under certain circumstances such as porous surface skins [17,25]. The water freezes and expands at low temperatures at high altitude and can thereby damage the honeycomb cells [17,25].

In addition to the time intensive manufacturing processes, prepreg/honeycomb based sandwiches have a considerable environmental footprint. The production of aramid/phenolic structures itself and the manufacturing of thermoset based sandwich structures has a negative impact on the environment and workers' health, due to the chemistry of the thermoset resin [22,26,27]. Furthermore, recycling concepts for thermoset based sandwiches are rare, leading to a negative environmental impact after service [22].

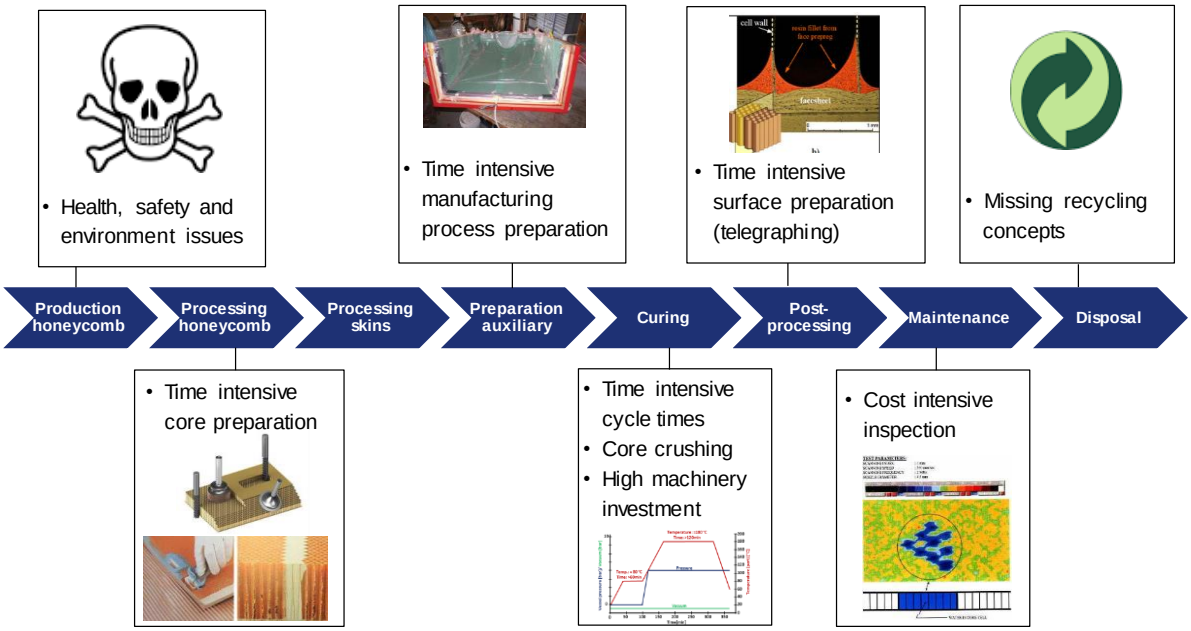


Figure 4: Negative influence of prepreg/honeycomb sandwiches on the DOC of aircraft and the environment during the life-cycle

1.1 MOTIVATION

According to [28] the demand of mobility, especially the demand for high speed traffic such as air traffic, will increase significantly until the year 2050. Airbus Helicopters expects a growth of 50 % in the world civil helicopter fleet in service over the next 20 years [29], and Airbus Commercial Aircrafts expects a demand for more than 33,000 new passenger and freight aircraft in this period [30]. However, the likely division of market share amongst the Original Equipment Manufacturers (OEMs) is hotly debated, and the competition is strong [31]. In order to stay competitive, OEMs need to provide aviation vehicles that have low design and manufacturing costs as well as being competitive in terms of operating costs, since in the end, operators are interested in cost savings throughout the lifetime of the product, i.e. low acquisition, operating and disposal costs [32]. The life cycle cost (LCC) analysis considers the cost of a product or system over its entire lifetime [33]. However, the aircraft operator is not particularly interested in LCC, but rather more in the direct operating cost (DOC), which can be described as

$$DOC = C_{flt} + C_{maint} + C_{depr} + C_{lnr} + C_{fin} \qquad \textbf{Equation 1}$$

C_{flt} = Cost(crew, fuel, insurance), C_{maint} = Cost(maintenance, repair, overhaul), C_{depr} = Cost(price, flight hours), C_{lnr} = Cost(landing and navigations fees, registry taxes), C_{fin} = Cost(financing strategy) [32].

In order to make an aviation vehicle competitive, the goal is to minimise the DOC. From an engineering point of view, crew costs, financing strategies, landing and other fees can be excluded [32]. The potential to reduce fuel consumption with weight savings has, for the most part, been exhausted by the application of sandwich structures. Any potential to increase the competitiveness of aviation vehicles hence lies in reducing the cost of acquisition by means of **reduction in production costs** and **reduction of maintenance and repair** during service.

Furthermore, besides this economic pressure, the environmental footprint of aviation vehicles is moving ever further into the spotlight. End of life solutions including recycling and dissembling solutions are being requested more and more by aviation vehicle operators, who need to cope with IS0 14000 requirements [34]. In his former position as CEO of Eurocopter (today Airbus Helicopters), Dr. Lutz Bertling highlighted that the **protection of the environment** is today at the heart of the company's innovation strategy [35].

Due to the lightweight potential of sandwich structures and based on the drawbacks of prepreg/honeycomb sandwich structures, it is not surprising that there is increasing demand for new cost-effective production technologies for sandwich structures to make the products more competitive in the future. In addition, due to increasing interest in reducing the environmental impact of aviation vehicles, there have been moves to replace environmentally harmful materials and processes with innovative, environmentally friendly materials and manufacturing techniques. However, any novel structures will have to fulfil the requirements without compromising on the weight advantage already achieved.

The introduction of thermoplastic materials for sandwich structures seems promising in lowering manufacturing costs, and lessening the environmental impact, and thereby in increasing the competitiveness of sandwich structures [22]. Thermoplastic materials are characterised by molecules chains associate reversibly through intermolecular forces (such as Van der Waals forces), which allow disconnection and thereby softening (melting) of the material by the input of heat, solvents or mechanical forces [36]. Material softening offers the potential to be thermoformed or fusion joined [37]. Cooling or removal of the solvent returns the polymer to a solid [38,39]. This property enables a more automated process chain including lower manufacturing costs compared to thermoset based structures. Additionally, the application of thermoplastic polymers improves recyclability and damage tolerance [22,38,40].

Thermoplastic composite (TPC) parts have been applied ever more frequently in aviation in recent years and further growth is expected [41]. For example, over 1000 individual parts, representing 7.5 percent of the aircraft's total composite airframe flyaway weight, have been incorporated into the A380 of Airbus. Meanwhile, up to 8000 parts have been realised as TPC structures in the A350 XWB, the newest model of the Airbus fleet [41]. Besides the possibility to manufacture thermoplastic composite in short cycle times by means of heat and pressure [42], thermoplastic materials and manufacturing technologies offer greater environmental benefits compared to commonly used aerospace materials over all of their life phases [43]:

- Less energy consumption for storage
- Less energy-consuming manufacturing technologies due to short cycle times
- Enhanced maintenance through easier disassembly and repair
- More possibilities for recycling

In addition to the introduction of thermoplastic materials for sandwich structures, it would seem advantageous to apply foam cores instead of honeycomb structures. Foam cores are already used in the aviation industry, though they find fewer applications than honeycomb structures. One good example for successful application of foam cores is Polymethacrylimide (PMI) foam in rotor blades [21]. In general, foam cores feature lower mechanical performance than honeycomb structures but they are cheaper, require less processing steps and allow more design flexibility due to their thermoformablity [5,23]. According to [44], the application of foams in sandwiches can reduce production cost by up to 30 %. Furthermore, closed cell foam cores

feature an even distribution of pores leading to isotropic behaviour and minimal water absorption, reducing the need for maintenance. Furthermore, telegraphing can be avoided by using foams [45]. Even though the structural performance of foams is inferior to that of honeycombs, a detailed comparison of several foam and honeycomb sandwiches for aviation applications revealed that foams do show advantages regarding their impact behaviour [45].

To tackle the manufacturing costs of sandwich structures and to reduce the environmental footprint of structural parts, the goal of this study is the development of a time-efficient and cost-efficient manufacturing process for thermoplastic composite sandwiches for structural helicopter applications. In addition, it is aimed to apply thermoplastic foam cores instead of honeycomb structures to further decrease manufacturing times and to reduce maintenance effort. To show the potential of the sandwich structures thus developed, technical and economic results will be assessed based on a comparison to state-of-the-art sandwiches, and according to requirements for structural sandwich parts. Finally, a three-dimensional (3D) demonstrator will show the feasibility of thermoplastic composite sandwich structures for formed applications in aviation.

1.2 REQUIREMENTS

Besides the motivation to reduce manufacturing costs and to lower the environmental footprint, it is important that newly developed sandwich structures fulfil diverse helicopter case specific requirements without suffering loss in their weight advantage. In general, sandwich structures find application in helicopters in two-dimensional (2D) as well as 3D sandwich components in external structural and internal parts, see Figure 2. To enable the possible application for every use case, the sandwich structures and materials should offer a high dimensional flexibility. This means, that the aimed sandwich structure should be realisable with different shapes and dimensions such as skin and core thickness, which are defined (based on existing structures) to be in the thickness range of 0.5 mm – 5 mm for the skins and up to 50 mm for the core. During service sandwich structures are exposed to different load cases. External structures have to withstand high operational temperatures (for example downwash of engine exhaust gases) and high aerodynamic loads. Internal structural structures must additionally meet FST requirements, and they also must withstand discrete loads caused by passengers, such as sharp stones under soles of shoes. For this study, it assumed that common carbon fibres used in aviation applications offer the required properties for skin laminates. Therefore, the focus for the skin materials is more on the fibre volume content (~58 vol % for unidirectional (UD) reinforced materials and ~55 vol % for fabric based skins) and the properties of the matrix material at elevated temperatures (135 °C). For the latter, the skin matrix material is required to have its glass transition temperature above 140 °C. Since the loads, which are acting on the sandwich, are transferred into the core, the skin-to-core bond strength need to be high. This strength can be evaluated based on the peel strength, which needs to be higher than 0.8 N/mm. Furthermore, the core structure itself need to feature high mechanical properties. While for example the weights of passengers lead to compressive loads perpendicular to skins, aerodynamic loads cause bending moments which lead to shear loads within the core. Based on experiences of actual applications and load cases, the core should feature a compressive strength at least of 1.4 MPa and a shear strength of > 1.1 MPa. Nevertheless, to limit the weight increase of the envisaged sandwiches in comparison to Nomex® based sandwich structures, the density of the foam core should be below 110 kg/m³. Furthermore, it is required

that core shows a low moisture absorption (< 2.1 %) to limit further weight increase and to avoid significant performance reduction under hot wet conditions.

Moreover, the structures need to show a high resistance against several chemical substrates such as cleaning agents, kerosene and hydraulic fluids. In order to improve the environmental impact and to protect the works heath during production, the material needs to be HSE conform. These requirements are much more stringent than requirements for automotive applications, where the mechanical performance and the thermal stability play a less important role. Automotive requirements focus more on weight and cost savings.

Table 2 gives a summary of the derived requirements, which are both application- and manufacturing-driven. This enables on the one hand the evaluation of state-of-the-art sandwiches and the selection of novel materials and processes. On the other hand, these requirements give indication for the manufacturing cycle time reduction, which is aimed to lie below 4 hours.

However, it should be noted that the work presented here is part of a research project on a technology that is at a low level of maturity. Therefore, the requirements can only be understood as an aid for decisions during the research activities, and not as final requirements for specific applications.

Table 2: Summary of requirements

	Criterion	Value	Unit	Standard
Skin	Skin thickness	0.5 – 5	mm	
	Fibre volume content	UD: ~58; Fabric: ~55	vol %	EN 2564
	Glass transition temperature	> 140	°C	T_g onset
Foam	Core thickness	10 – 50	mm	
	Core density	< 110	kg/m³	
	Moisture uptake	< 2.1	%	
	Glass transition temperature	> 140	°C	
	Compressive strength	> 1.4	MPa	DIN 53291
	Core shear strength	> 1.1	MPa	DIN 53294
Sand-wich	Skin-core drum peel strength (foam)	> 0.8	N/mm	DIN EN 2243-3
	Residual compressive strength after impact (CAI 5J)	> 150	MPa	AITM 1.0010
Process-ing	Processing temperature	< 400	°C	
	Target cycle time	< 4	h	
In-service	Media resistance against	Kerosene, hydraulic fluid, cleaning agents, etc.		
	Painting	Yes		
	UV-resistance	Yes		
	FST requirements	(UL-94 V-0)		
HSE	Components to be avoided that are	Toxic, mutagenic, carcinogenic		
	Disposal	Recyclability, re-use		

2. STATE OF THE ART

Thermoplastic composite (TPC) sandwich structures promise to be advantageous for more than just the aviation applications, therefore they have been investigated in the past by different researchers for the automotive and rail industry.

In order to identify suitable manufacturing methods for thermoplastic sandwich structures in aviation applications that require the use of so called “high performance thermoplastics”, a review of the public literature on manufacturing methods for thermoplastic sandwich structures is conducted. Firstly, thermoplastic skin and core materials, applied in investigations as well as in commercial products, are presented. Secondly, the manufacturing methods for flat, two-dimensional (2D) sandwich structures, investigated by different researchers, are presented and discussed in detail. Thirdly, manufacturing approaches for three-dimensional (3D) thermoplastic composite sandwiches are reviewed separately. Finally, analytical modelling approaches which describe and investigate the joining and forming process of thermoplastic sandwich structures are presented.

2.1 MATERIALS

2.1.1 Skin material

Skins for TPC sandwiches consist of fibre reinforced laminates with a thermoplastic matrix in which either short or continuous fibres are used. Thermoplastic composite skins are available as fully consolidated laminates, semi-prepregs or prepregs. The thermoplastic matrix polymers in general range from commodity plastics such as Polypropylene (PP) or engineering polymers such as Polyamide (PA) to high performance polymers such as Polyetherimide (PEI) or Polyetheretherketone (PEEK). Table 3 gives an overview of thermoplastic composite sandwich skin materials reported in the published literature. Commodity plastics in combination with reinforcing glass fibres are mostly employed as skin materials for TPC sandwich structures. Especially PP based composites are applied that are traded under the Twintex® name. This can be explained by the low price of the material and the ease of processability of PP since most investigation have been performed for automotive application where manufacturing times need to be reduced drastically [46,47]. The most widely applied high performance polymer in TPC sandwich skins of interest to the aviation industry is PEI, often combined with reinforcing glass fibres.

2.1.2 Core material

Sandwich cores are usually of lower density than the skin materials and can be classified into three classes, according to their architecture, see Figure 5: corrugated or truss core (a), foam or solid core (b), honeycomb core with hexagonally shaped cells, circular or square cells (c) [4]. The core types most commonly described in the investigated literature are thermoplastic foams or honeycomb cores, both utilising different kinds of thermoplastic polymers such as PP or PEI (see Table 4). Honeycomb structures in general feature better performance in terms of strength and stiffness than foams, though they are often more expensive as illustrated in Figure 6 [5]. Thermoplastic honeycomb structures can be produced via different routes. One kind of thermoplastic honeycomb structure is realised by the use of thermoplastic tubes, which are bonded to each other at their sides [48].

Table 3: Overview of thermoplastic composite materials applied as sandwich skins as reported in public literature

Application	Polymer	Reinforcement	Fibre content*	Trade name	Supplier	Reference
Automotive, rail or food packaging applications	PP	Glass fibre mat (GMT)	40 wt %,	GCMP®40	Georgia Composite, Inc., USA	[49]
	PP	Short random fibres	30 wt %, 23 vol %	/	Quadrant Composites, Switzerland	[50]
	PP	Glass fibre mat	50 wt %	/	Montell Italia, Italy	[39]
	PP	Continuous glass fibre		/	Advanced Composite Systems, Austria	[51]
	PP	Glass fibre unidirectional	60 wt %	/	/	[52,53]
	PP	Glass fibre fabric	/	/	/	[54,55]
	PP	Glass fibre fabric	60 wt %, 35 vol %	Twintex®	Saint Gobain Vetrotex, France	[40,46,47,49,50,56–64]
	PP	GMT /Continuous glass fibres	40 wt %,65 wt %	Plytron®	/	[65]
	PP	PP fibre	> 90 vol %	/	/	[50]
	PA	Glass fibre fabric	52 vol %	Vestropreg®	Hüls, Germany	[62,66–70]
	PA	Glass fibre knit	50 wt %	/	/	[62]
Aviation applications	PEI	Glass fibre warp knitted fabric	27.5 vol %	/	Tencate, Netherlands; Tec-Knit, Germany	[71–74]
	PEI	Glass fibre fabric	50 vol %	Cetex®	Tencate, Netherlands	[37,75–80]
	PEI	Carbon fibre fabric	50 vol %	Cetex®	Tencate, Netherlands	[37]
	PEEK	Carbon fibre unidirectional	68 wt %	Thermo-Lite®	Phoenixx TPC, Inc. USA	[81]
	PPS	Glass fibre fabric	50 vol %	/	/	[80]

* wt = weight, vol = volume

During production, a coating made of an adhesively-active thermoplastic material is applied to the outside surface of the tubes in a co-extrusion process. Then the tubes are lined up alongside each other. By thermal treatment under pressure in a subsequent processing step, the coating is activated and the tubes are joined after cooling [48].

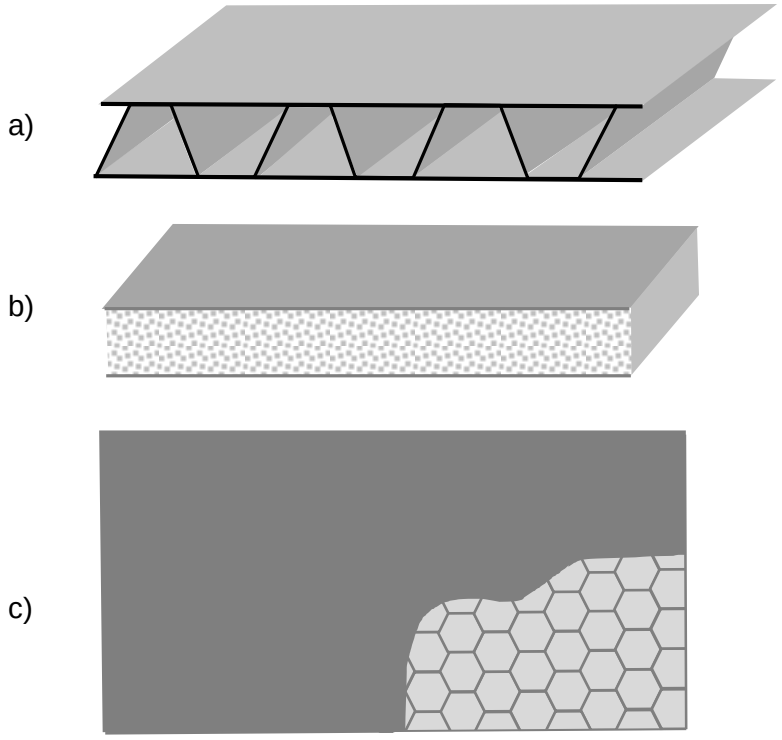


Figure 5: Different core types: a) corrugated core, b) foam core, c) honeycomb core [4]

Another production method for thermoplastic honeycombs is described in patent US4957577 [82]. The honeycomb structure consists of thermoplastic strips which are welded selectively at nodes and expanded to hexagonal cells. In the first step, two thermoplastic strips are superimposed on one another throughout their entire length. The strips are fusion bonded together at evenly spaced nodes by ultrasonic welders. Subsequently, more strips are welded one by one, on top, to a bundle of film strips in accordance with step one. Release films are placed in-between the strips to ensure that welding only occurs at the designated spots. After all welds have been completed, the bundle of strips is exposed to heat. Reaching the softening temperature of the thermoplastic material, the bundle of stripes is expanded to form hexagonal cells and cooled afterwards while holding the web in the expanded position to rigidify the honeycomb configuration [82]. Another manufacturing process is known as the ThermHex® concept [83]. The core structure can be produced on one production line in a continuous process. Starting from an endless thermoplastic foil, a half-hexagonal web is formed by deep drawing or vacuum forming. This half hexagonal web is then folded to build the honeycomb core followed by internal bonding of the cell walls. In a subsequent step, the skin laminates can be directly fusion bonded to the core [83]. Meanwhile, an origami-like core is traded under the name Foldcore®, which is folded from a planar base material into a three-dimensional structure [84]. Foldcores® can be produced from papers, metals and any kinds of thermoplastic foils [85]. In the next generation fibre reinforced thermoplastic Foldcores® are envisaged.

Foams show lower mechanical properties than honeycombs, though they feature some advantages such as acoustic damping and thermal insulation [5]. Additionally, thermoplastic foams exhibit good thermoformability.

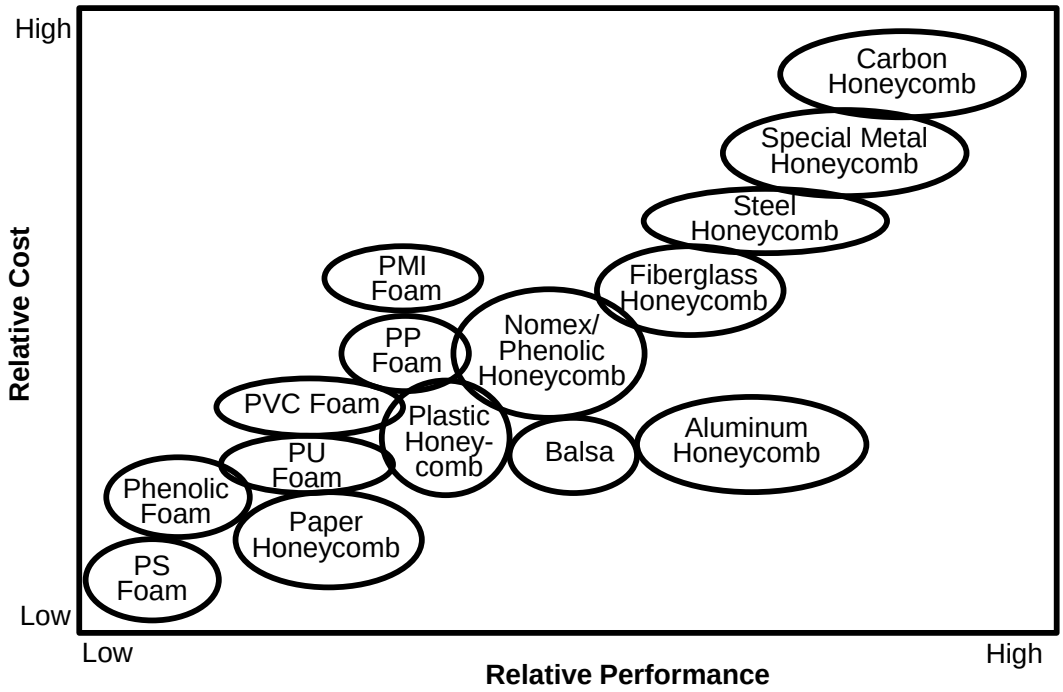


Figure 6: Cost versus performance of core materials according to Campbell [5]

Foam, more specifically polymeric foam, is the term for cellular structures made out of polymers in the form of cell walls and webs as well as foam cells filled with gas [86]. Foams can be classified by several characteristics, where density and cell structure are considered to be some of the most important properties [86]. Since foams with an open cell structure usually feature low mechanical performance, they do not play a significant role in terms of structural parts such as sandwiches. A detailed overview of foam classifications is given in [87]. Several manufacturing methods such as extrusion or injection moulding, etc. can be used to produce foams [87]. Foam cores are made by using a foaming or blowing agent that expands during manufacturing and realises a porous, cellular structure. In doing so, the production of polymeric foams can be divided into five physical steps: dispersion of blowing agent, homogenisation, cell nucleation, cell growth and stabilisation [86]. For thermoplastic polymers, the following commercial processes enable the production of foams: foam extrusion offers the ability to produce blanks, films, as well as gas-loaded or foamed particles. Foamed particles can be further processed into particle foams. Injection moulding enables the near-net shape production of parts and integral foams [86]. In-situ film foaming refers to a technology where the foam is built up from a blowing agent loaded film, which expands in-situ during the sandwich production process [76]. Theoretically, almost any polymer can be used to produce foams by adding an appropriate blowing agent [5], however the production of semi-crystalline thermoplastic foams entails major challenges. The crystalline microstructure is considered to be the main reason for its challenging processing, allowing only a small process window for processing [88]. An overview of the core (foams and honeycombs) materials and structures described in the reviewed literature is given in Table 4.

Table 4: Overview of materials used in thermoplastic sandwich cores as reported in public literature

Application	Structure	Polymer	Density (kg/m³)	Tradename	Supplier	Reference
Automotive, rail or food transport	Foam	PP	60,64,96	Strandfoam®	Dow Automotive (Chemical Company), USA	[40,49,59,60,63,65,89]
	Foam	PP	100	RPF	Sekisui, Japan	[50]
	Foam (Particle foam)	PP	40,60,80	EPP, Neopolen®	BASF SE, Germany	[57,65]
	Foam	PP	90,100	/	Kaneka, Belgium	[61,89]
	Foam	PP	100	/	Montell Italia, Italy	[39]
	Foam	PP	/	Armourlite® FST	/	[56]
	Foam	PET	80,110	Divinycell® P	Diab, Sweden	[46,58]
	Foam	PET	75,109,156	Cobifoam 0	Mossi & Ghisolfi S.p.A Italy	[133]
	Foam	PA12	/	/	/	[91]
	Foam	PMI	52,70,75,110	Rohacell®	Röhm (Evonik), Germany	[56,64,66–70]
	Foam	PES	/	Ultratec®	Advanced Composite Systems, Germany	[51]
Aviation	Foam	PET		Divinycell® P	Diab, Sweden	[80]
	Foam	PES	90	Divinycell® F	Diab, Sweden	[80]
	Foam	PEI	60,80	Airex®	Airex AG, Switzerland	[64,71–73,80]
	Foam (in-situ foamed)	PEI	80-240	FITS panel, Dynatech	FITS-technology, Netherlands;SMTC,France	[75,76,78,91,92]
	Foam	Carbon	380	KFoam	Koppers, USA	[81]
Automotive, rail	Honeycomb	PP	80	PP30-5-1	Plascore®, Germany	[49]
	Honeycomb	PP	43,80,120	Wavecore®	Tubus Bauer, Germany	[49,50,61,90]
	Honeycomb	PP	110	Nida-core®	/	[49]
	Honeycomb	PP	60,80	Nidaplast®	Nidaplast, France	[52,53,65]
	Honeycomb	PP	80,120	/	/	[47,93,94]
	Honeycomb	PA12	94	/	Hüls, Germany	[69]
Aviation	Honeycomb	Aramid/Phenolic	/	Nomex®	DuPont, USA	[37,79]

Table 4 illustrates that mostly commodity plastics such as PP or Polyethylenterephthalate (PET) are applied as foam core structures for automotive or rail applications, which can be can be explained by cost reasoning [47], availability [49] and the aim to realise sandwich structures which consist only of one polymer throughout the whole sandwich for recycling reasons [50]. It is also obvious that Polymethacrylimide (PMI) cores, traded under the name Rohacell®, are used by a number of researchers. Although PMI cannot be melted, which defeats the recycling concept for all-thermoplastic sandwiches, the high temperature resistance of up to 180 °C in combination with its thermoformability makes PMI attractive for application in TPC sandwiches [38,95]. In the area of high performance thermoplastic polymers, Polyethersulfone (PES) and especially PEI cores are favoured. With an operation temperature of up to 180 °C and excellent FST (Fire, Smoke & Toxicity) properties, PEI is an interesting material for the aviation industry [96,97]. In comparison to other core materials, PEI cores often originate during the production (in-situ) of the sandwich structure. Due to the combination of a PEI film with a blowing agent, the material expands under heat treatment [75,76,91]. Furthermore, Table 4 illustrates that cores with a density in the range of 40 kg/m³ - 380 kg/m³ are utilised, with a trend towards lower densities < 110 kg/m³.

In the case of thermoplastic honeycomb cores mainly PP is used for automotive applications. This can be as well explained by cost reasoning, availability and the aim to realise a single polymer sandwich. Furthermore, some researches combine thermoplastic skins with the Nomex®-honeycomb, which is well established on the aviation market.

2.2 SKIN-CORE JOINING

In order to produce a TPC sandwich structure of sufficient quality, a good bond between skins and core needs to be achieved. A good bond between skins and core is defined as a bond which does not represent the weakest link within the sandwich structure and which allows the transition of forces between skins and core [4,6]. The following Figure 7 gives an overview of different skin-to-core joining techniques for thermoplastic composite sandwich structures, which have been investigated in the past. The processes for skin-to-core joining can be divided into two main groups: adhesive bonding and fusion bonding. Several processes for adhesive and fusion bonding of skin and core have been described in the public literature. These processes as well as some commercial technologies and products are presented in the following sections.

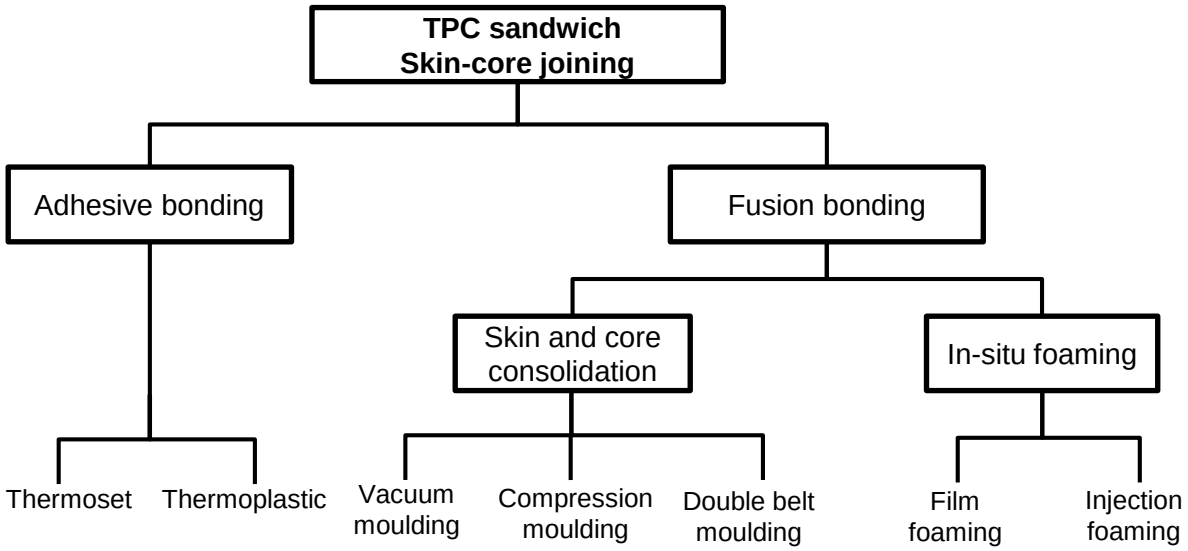


Figure 7: Processing routes for skin-to-core joining of TPC sandwiches

2.2.1 Adhesive bonding

2.2.1.1 Thermoset-based technologies

Joining of thermoplastic composite skins and a thermoplastic core can be achieved by the use of a supplementary material such as a thermoset-based adhesive film, in which experience gained from bonding of monolithic composite structures can be beneficial. A fundamental look into adhesive bonding in general is given by Pizzi and Mittal [98]. Campbell [5] presents an insight into adhesive bonding of monolithic composites as well as composite sandwich structures for aerospace applications. TPC sandwich structures can also be joined with similar epoxy based adhesive materials. For example, Rozant et al. [71,73] applied a 150 g/m² epoxy film to combine glass fibre reinforced PEI skins with a PEI foam core. Offringa [37,79] describes TPC sandwich applications for aircraft floor panels, where PEI fibre reinforced laminates are adhesively bonded to a Nomex®-honeycomb core. This joint is also created by a structural epoxy adhesive film. However, in order to achieve a good bond with thermoset adhesives contaminants present on the components surface, such as release agents, machine oils or fingerprints, first need to be eliminated [99,100]. Additionally, surface treatments can ensure an improvement of the bond strength caused by wetting improvement of low energy surfaces, chemical modification of surfaces or by increasing the surface roughness [100]. Typical surface treatments for composites such as plasma treatment or grit blasting are presented by Wingfield [99]. To this end, Haslam [101], for example, studied different surface treatment/adhesive material (e.g. epoxies or urethanes) combinations to enable bonding between Polypropylene or Nylon composites and balsa wood or Polyurethane foam cores.

Adhesive bonding is generally considered time and labour intensive, due to extensive surface treatment and long curing cycles involved (e.g. 90 minutes at 110 °C for 3M Scotch Weld Structural adhesive film AF163-2 [102]) [100]. Additionally, this concept often causes a relatively weak skin-to-core bond for thermoplastic materials, since the chemical and physical compatibility between the adhesive material and the skin and core is generally not ideal [22].

Moreover, thermoplastic materials often feature low surface energies, making wetting of the surfaces by an adhesive difficult [99,103].

2.2.1.2 Thermoplastic-based technologies

Another approach for adhesive joining of skins and core can be realised by applying thermoplastic hot melt films [100]. The polymer film is placed between skin and core, softened for example by heat and finally solidified by cooling with the result that the film functions as an adhesive glue [50]. In the case of modified thermoplastic hot melt films, heating techniques such as microwave activation are also possible to soften the polymer [104]. The thermoplastic adhesive hot melt concept is considered a faster (no curing has to take place) and eco-friendlier alternative (possible recycling by disassembling after re-heating) in comparison to thermoset based adhesive materials [98,100]. Additionally, joining by means of hot melt adhesives offers the advantage that dissimilar polymers/substrates can be combined [105].

Usually thermoplastic hot melt films possess a lower softening temperature than core and skins [50]. Skins and core stay in the solid state during the joining process with the result that interdiffusion of the molecules of skins and core does not take place. The joining process is controlled by the heating temperature, pressure and consolidation time. To obtain a fully recyclable thermoplastic sandwich structure, Cabrera et al. [50] developed an all-Polypropylene (PP) sandwich panel. They applied a low sealing temperature PP copolymer film to adhesively bond PP self-reinforced and glass fibre reinforced PP laminates to PP foam and honeycomb cores. At processing temperatures between 135 °C and 145 °C and a pressure of 0.04 MPa, sandwich skins were successfully joined to the core without influencing the structure of either the core or the skins. The sandwich specimens were manufactured in a press or with a vacuum setup. The skin-to-core bond was tested by means of a peel test. It was shown that the application of a hot melt film improved the face to core bond compared to sandwiches without a hot melt adhesive. Average peel forces per width of approximately 8 N/cm could be achieved for the foam and the honeycomb sandwiches. Pappada et al. [46] tried to improve the core-skin interfacial bond of glass fibre reinforced PP skins and a PET foam by integrating a low temperature melting PET film. By means of either vacuum bagging or compression moulding, the film was melted at temperatures of 160 °C to 180 °C where skins and core were joined under pressure. The samples were tested by means of an adapted three-point bending test. An elevated pressure of 0.2 MPa realised with a press led to better results than achieved with vacuum pressure, due to the limited flow capability of the hot melt film under low pressure. The average interfacial fracture energy for the specimens produced by means of the press amounted to 110 J/m².

An example of a commercial sandwich product manufactured by means of a thermoplastic hot melt film is the Cetex®System3® by Tencate and Tubus Bauer [106]. A copolyester thermoplastic adhesive is placed in between the fibre reinforced PEI skins and the PEI honeycomb core. An excellent bond can be achieved when the stack is heated to 150 °C, a temperature that does not alter the PEI components. The System3® sandwiches feature peel strengths of 5.07 N/mm when tested according to EN 2243-3.

Melting only one component of the sandwich, preferably the skins, and realising the bond based on mechanical interlocking between the surfaces is another way to achieve a thermoplastic adhesive bond between skins and core [67]. Here, thermoplastic composite

skins possess a lower softening temperature than the core structure [51,64,66,70]. Nowacki's prototype [64] of a seat structure can be taken as an example, since it consists of glass fibre reinforced PP skins (Glass transition temperature T_g = -10 °C, Melting temperature T_m = approx. 170 °C [107]) and a PEI foam core (T_g = 215 °C [107]). The skin polymer is heated and softened followed by applied pressure, which forces the molten polymer of the skins to flow into the surface cells of the foam core [70]. After solidification of the skin polymer, mechanical interlocking is obtained and an adhesive bond is created [67]. Since an increased amount of polymer along the skin-core interface improves the bonding strength, the application of additional polymer at the interface material seems to be beneficial [22,67]. Thermoplastic sandwich structures based on Polyamide 12 (PA12) composite skins and PMI foam cores are produced according to this method by some researchers [66,69,70]. McGarva et al. [38,66,67] consolidated glass fibre reinforced PA12 skins on a PMI foam core. The skins were heated to 180 °C – 280 °C to soften the polymer matrix, which was then forced under pressure of 0.25 MPa – 1.75 MPa to flow into the cells of the PMI core. The PMI core was compacted during this process, though not molten. Therefore, bonding of skins and core is only based on adhesive forces on the surface. The modified double cantilever beam test was applied to determine the critical strain energy release rate G_C, which indicates the degree of skin-core bonding. McGarva found that adding a separate pure PA12 film into the interface improves the skin-to-core bond, since a larger amount of PA12 is available to flow into the cells. Strain energy release rates of up to 0.8 N/mm were achieved [67]. Breuer et al. [69] produced 3D (hemisphere shape) PA12/PMI thermoplastic sandwiches in one step. PA12 based skins and a PMI core were stacked during heating and then joined and formed into a 3D part in less than one minute. Breuer showed that temperature control during heating is essential to keep the temperature of skins and core within the process window. The optimal heating temperature was determined to be between 180 °C – 190 °C for the PMI and 185 °C – 210 °C for the PA12 composite skins.

Brown et al. [56] applied the vacuum bagging technique to combine glass fibre reinforced PP laminates with a PP nanocarbon or PMI core. Skins and core were assembled in glass prepreg tools and consolidated at 190 °C for 3 hours. BASF SE released a press report [51] on a sandwich structure, which finds application as an automotive seat. Heated glass fibre reinforced PP skins were joined with a cold Polyethersulfone (PES) foam core in a press. Reyes et al. [81] described carbon fibre reinforced PEEK skins that were combined with a carbon-foam (Kfoam by Koppers, USA). Carbon fibre reinforced PEEK-plies, separate layers of pure PEEK and the carbon foam were placed in a mould, which was heated to 380 °C for about 10 minutes. Then the mould was transferred to a cold press, which applied a pressure of 1.75 MPa until the mould was cooled down to ambient temperature. The bond between the PEEK based skins and the carbon foam is created by interlocking of the PEEK polymer and the pores of the cellular core. Interfacial fracture energies of up to 170 J/m² were obtained by testing the sandwiches by means of a single cantilever beam test. Mühlbacher et al. [80] joined glass fibre reinforced PPS skins with PET and PES foam cores, but a strong bond could not be achieved. The manufactured samples failed adhesively with bond strengths which were significantly lower than the core strength itself. The low bonding strength is explained by degradation effects on the PPS skin surfaces, which complicate and hinder adhesion between skin and core.

2.2.2 Fusion bonding processes

Another approach to join thermoplastic skins and core is fusion bonding. This process is only suitable for thermoplastic materials and is characterised by a joint formed by intermolecular diffusion of the polymers of the components, also referred to as adherents, to be joined [108]. This is opposed to adhesive joining, where the joint is created by mechanical interlocking of the two dissimilar substrates on the surface. Fusion bonding, also called welding, is a well-established joining process for thermoplastics, and different technologies for joining thermoplastic composites have been studied by various researchers. An overview is given by Ageorges in [100]. Due to the interdiffusion of the molecules, the joint can approach the bulk properties of the adherents [109,110]. Additionally, fusion bonding can be performed in short cycle times and needs only nominal surface treatment [111].

Fusion bonding of thermoplastic materials can be explained by the ‘autohesion’ or ‘self-adhesion’ theory [112]. According to this theory the bonding occurs when the polymer molecules near the surface become mobile and the bond is developed through a combination of surface rearrangement, wetting, diffusion and randomisation of the polymers, see Figure 8 [113].

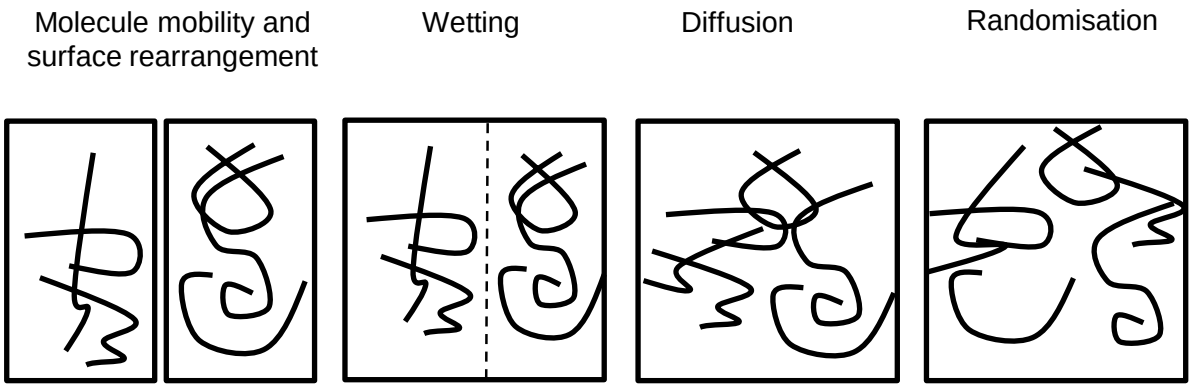


Figure 8: Fusion bonding model according to Akermo et al. [6]

In some applications, e.g. packaging, a combination of different polymers is required [114]. Fusion bonding of two or more chemically different polymers poses some challenges, since it requires miscibility of the polymers [115]. It is often not even possible to join two dissimilar polymers by means of fusion bonding [115]. Interdiffusion of the molecules is highly influenced by the temperature, composition, miscibility, molecular weight distribution, chain orientation and molecular structure of the adherents [113,115,116]. In addition, the mechanical properties, such as strength at the interphase can be affected when the combination is not ideal [113,116]. With the same polymer in both adherents resulting in interdiffusion of chemically coinciding molecules, the fusion bonded interface can achieve the bulk properties of the material [22]. Furthermore, sandwiches containing one single polymer in skin and core offer recycling potential (scrap and components) or even possibilities for postforming [22,53].

In theory fusion bonding of thermoplastic composite skins and thermoplastic core structures with the same polymer should be readily possible according to the ‘autohesion’ theory [22,39,57]. However, several researchers have highlighted some challenges. To ensure molecular interdiffusion between the core polymer and the skin polymer, the skins as well as

the core, more precisely the core surface, need to be molten. By applying pressure to achieve intimate contact the core can be compacted due to its low density or can collapse due to extensive heating [22,40]. In order to prevent this, only a small process window exists to establish a good bond between skin and core [40,69].

2.3 MANUFACTURING TECHNOLOGIES FOR TPC SANDWICHES

In the following section technologies for producing a skin-core fusion bond, investigated in the public literature, are described. Most publications focus on the manufacturing of 2D sandwich panels. The investigations and manufacturing processes for production of 3D sandwich parts are mentioned in an additional section. The manufacturing technologies for 2D structures can be categorised as

- Vacuum moulding
- Compression moulding
- Double belt laminating
- In-situ foaming

2.3.1 Vacuum moulding

In the vacuum moulding process a stack of skins, core and potentially interlayer films are placed between a tool and transfer plate and sealed under an impermeable membrane as shown in Figure 9 [60]. The air under the impermeable membrane is evacuated with the result that the ambient pressure presses the single components together. To bond the parts together according to the ‘autohesion’ process, heat has to be applied to soften the thermoplastic matrix of the skins and core [40]. Moreover, a breather-material to guarantee uniform air flow is used. An additional release film eases the removal of the moulded sandwich after the process. The manufacturing setup is adapted from the manufacturing method for thermoset based sandwich structures [40].

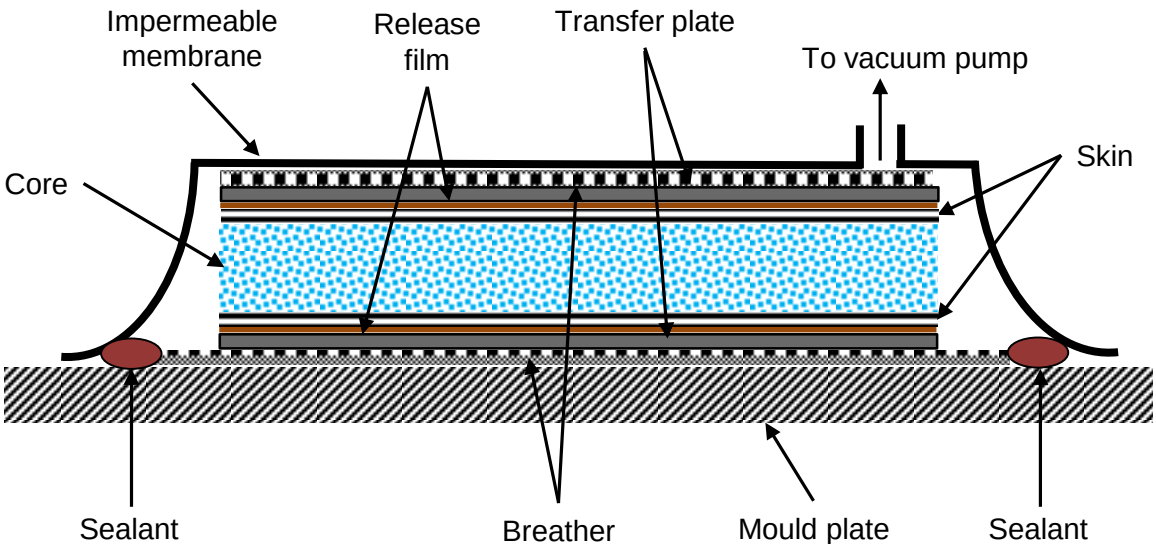


Figure 9: Vacuum moulding setup

According to Skawinski et al. [57], the heating of the sandwich components can be conducted isothermally or non-isothermally. The process is called isothermal when the whole stack is heated and pressure is applied simultaneously [57]. For a certain time, both skin and core have

a constant (isothermal) temperature. The temperature evolution during isothermal processing is illustrated in Figure 10a. The main process parameters are the heating temperature, the heating/holding time and the pressure. Isothermal vacuum moulding is characterised by a simple setup and basic equipment, though the chance of core collapse is high due to heating of the whole core. In fact, no public literature about fusion bonding by means of isothermal vacuum moulding is noted, though the process is applied in thermoplastic composite sandwich manufacturing by means of a hot melt adhesive (refer chapter 2.2.1).

Separation of the heating process from the bonding process is referred to as non-isothermal [40,57]. First, the skins are heated in a separate stage, e.g. an oven, then combined with the core (often a cold core is used) and transferred to a vacuum table using transfer plates [40]. The core, especially the core surface, is heated by conduction from the skins. Figure 10b illustrates the heat evaluation during processing. The vacuum bag membrane is sealed around the stack, the air is evacuated and the sandwich is consolidated [59,60,89].

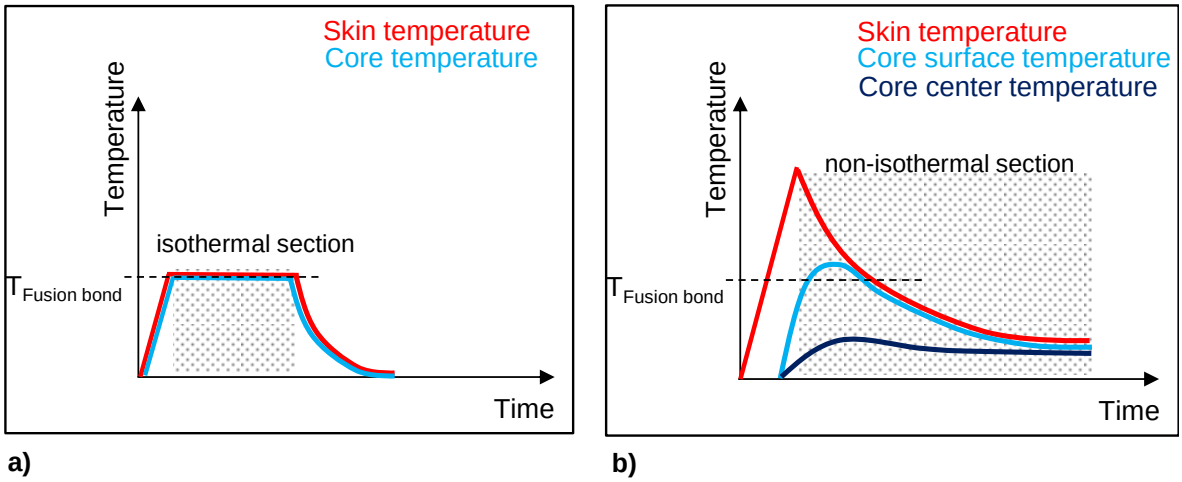


Figure 10: Temperature evolution during a) isothermal and b) non-isothermal TPC sandwich manufacturing

In comparison to the isothermal method, this process can be regulated by different parameters. The most significant variables are the skin pre-heat temperature, mould or vacuum table temperature, moulding time and vacuum moulding pressure. Other parameters are the transfer time, skin thickness, transfer plate characteristics and core pre-heat temperature [40]. The main advantage of the non-isothermal process is that the core is only heated at the surface when sandwiched with the hot skin, which reduces the likelihood of core collapse. Kulandaival et al. [40,59,60,63,89] investigated the process window for manufacturing a TPC composite sandwich consisting of glass fibre reinforced PP skins and a PP foam core by means of non-isothermal vacuum moulding. The pre-impregnated skins were heated up to approximately 180 °C – 220 °C in a hot air oven to ensure homogenous heating. Pre-heated (180 °C) transfer plates were used to minimise a temperature drop of the skins during the stacking process and the transport to the vacuum table. A low vacuum pressure of 0.6 bar – 0.95 bar sufficed to consolidate both skins and the skin-to-core interface. Kulandaival showed that the skin thickness and the skin pre-heat temperature are the most influential processing parameters for a successful skin-core bond [40,63]. Testing of the sandwiches resulted in approximately

16.5 MPa interlaminar shear strength (ILSS) for the skins and 730 N peak load in three-point-bending of the sandwich.

2.3.2 Compression moulding

The term compression moulding is used when the sandwich is manufactured in a mould by means of a press. Compression moulding is an industrially applied method for producing thermoplastic composites and thermoplastic composite sandwich structures [38]. Skins and core are stacked and placed in a mould before pressure is applied by a press. However, the comparatively low mechanical properties of the light weight cores limit the application of pressure [65]. As with vacuum moulding (refer to chapter 2.3.1), heating can be conducted isothermally (heating the whole stack while applying pressure) and non-isothermally as illustrated in Figure 11 (separate heating of the components before skin-core consolidation) depending on the heating method [38,57]. Similar to vacuum moulding, the main parameters for isothermal compression moulding are the heating temperature, moulding time and pressure. By separating the heating procedure from the bonding process, the non-isothermal compression moulding process can additionally be controlled by the skin and core pre-heating temperature and transfer time. Compression moulding was applied on PP based skins and PP core sandwiches by several researchers [39,49,57,65].

Skawinski et al. [57] compared isothermal and non-isothermal compression moulding processes for the manufacture of TPC sandwiches consisting of glass fibre reinforced PP composites and PP foam cores. He found non-isothermal compression method unsuitable for the manufacturing of TPC sandwiches because of poor skin-to-core bonding and a low skin surface quality. Rapid cooling of the pre-heated skins during transport prevented skin-core fusion bonding. In contrast, isothermal compression moulding led to successful production of sandwich parts which withstood tensile loads of approximately 3 kN. Total core compression could be prevented by the choice of an initially thicker core, which was compressed during the process [57].

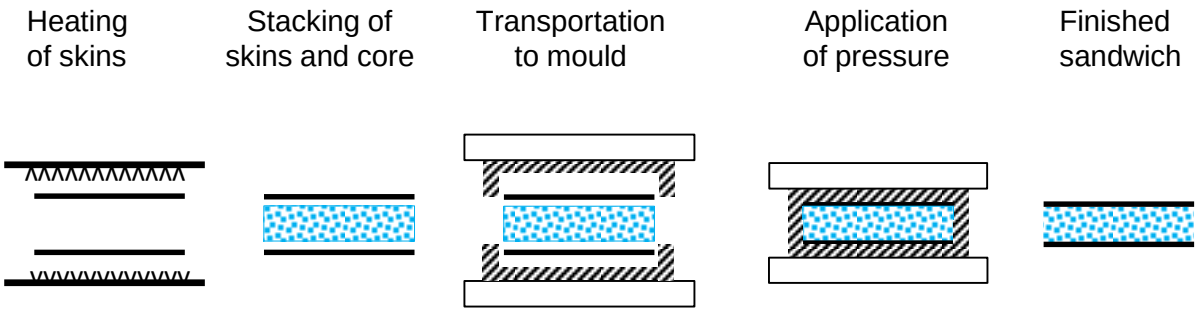


Figure 11: Non-isothermal compression moulding process according to McGarva [38]

Reynolds et al. [65] applied the non-isothermal compression moulding process for manufacturing flat panels as well as slightly curved sandwich beams. Glass fibre PP based mat thermoplastics (GMT) were combined with continuous glass fibre reinforced PP tapes for the skins. For the core structure two different PP foams and one PP honeycomb structure were investigated. The skins were heated in an infrared field, combined with a cold core and transferred to the mould, pre-installed in the press. The press was closed and pressure was applied. At the beginning of the fusion bonding process the skin-core interface reached a

maximum temperature of 170 °C before cooling down. After approximately 50 seconds, the skin-core interface was cooled down below 100 °C, which enabled demoulding. The mechanical performance of the sandwiches was investigated by means of a three-point bending test. Peak loads of up to 12 kN were achieved.

Akermo et al. [39] performed a detailed study with different settings of skin pre-heat temperature, moulding pressure, moulding time, forming rate and mould temperature for fusion bonding of glass fibre reinforced PP laminates and a PP foam core by non-isothermal compression moulding. Shear testing, transverse tensile testing, flexural testing and sandwich thickness measurements were chosen for the characterisation of the sandwich specimens.

Muzzy et al. [49] investigated the flexural rigidity and the impact properties of sandwiches based on glass fibre mat reinforced PP skins and PP honeycomb cores, for which they made use of a two-step non-isothermal compression moulding process. In the first press the skins were heated sufficiently high to melt them, before being stacked and consolidated with the core in a second cold press.

Kulandaivel [40] applied the non-isothermal compression moulding technique to produce reference sandwiches for comparison of vacuum moulded sandwiches (refer chapter 2.3.1). He pursued two different compression moulding techniques: In the multi-step method, the skins were fully pre-consolidated prior to being re-heated and moulded together with the core. Pre-heating stacks of PP based pre-impregnated products, which were simultaneously consolidated and fusion bonded to the core, was considered a single step method. In both cases Kulandaivel applied mould stops to control the compaction of the core. The single step compression moulding methods provided the best results (ILSS ~ 18 MPa, 830 N peak load), although the skin quality was inferior to that which can be achieved in compression moulded TPC laminates. Re-heating the laminates during the multistep compression moulding methods led to lower mechanical performance caused by degradation of the material as a result of excessive heating. Passaro et al. [61,89] also investigated one-step and two-step non-isothermal compression moulding with either PP foam core or PP honeycomb cores. The investigated parameters were core pre-heating temperature, pressure and press platens temperature. Moreover, the influence of an extra PP film layer (thickness up to 450 µm) in the interface on the bond quality was observed. The one-step process led to 20 % better tensile strengths than the two step-process (1.2 MPa tensile strength), bringing additional advantages such as time and energy saving. Pressure and thickness of the extra PP-layer turned out to be the most significant parameters.

Venture Peguform, France [47] uses the non-isothermal compression moulding process for the production of PP based sandwich Sandwiform® panels. The pre-stacked skins and core are heated in an infrared (IR) oven before being transferred to a press. There, the sandwich is stamped in a cold tool at 10 bar pressure.

Mühlbacher et al. [80] describe fusion bonding investigations on glass fibre reinforced PEI skins with PEI and PET foam cores realised by non-isothermal compression moulding. Although different materials in skin (PEI) and core (PET) are used, a fusion bond can be created since both materials are miscible [117]. Mühlbacher et al. [80] show the promising properties of the thermoplastic sandwiches by tensile, climbing drum-peel and 4-point bending testing, which can be realised in short cycle times below 4 minutes and compared the results

to Nomex® based sandwiches. However, the thermoplastic sandwich structures are limited to thin skin materials, which fail during 4-point bending in the area of the loading spans.

2.3.3 Double-belt laminating

A continuous production of thermoplastic composite sandwiches based on fusion bonding can be performed by a double-belt laminator [62,118]. The process is considered efficient and cost-effective since the continuous production enables speeds of several meters per minute [119]. First skins and core are automatically stacked, before entering a group of contact heating elements. The sandwich stack is heated and fusion bonded under pressure. Then a group of cooling elements solidifies the sandwich under pressure, see Figure 12. During the process the temperature needs to be monitored to avoid overheating which could lead to core collapse. After the consolidated sandwich leaves the double-belt laminator it can be cut into individual pieces [90,118].

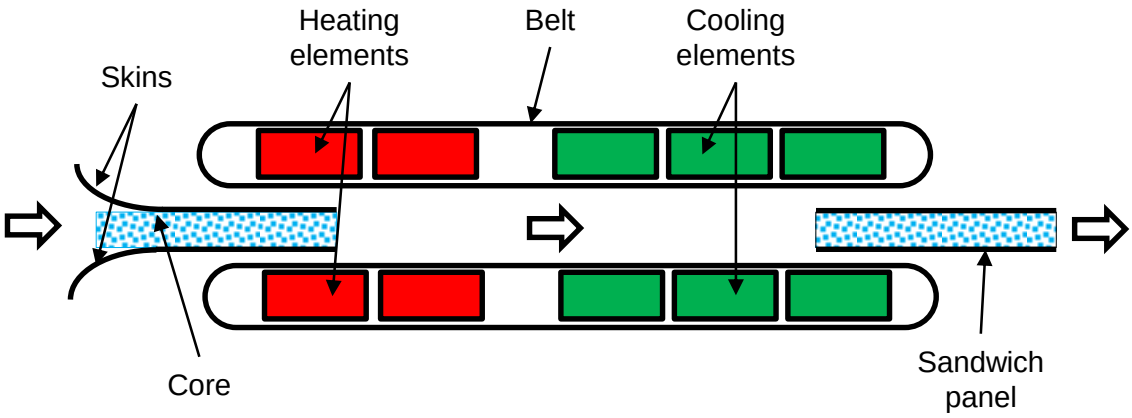


Figure 12: Double belt laminating accorting to Fan et al. [90]

Process variables such as material type, thickness and belt speed, pressure as well as heating and cooling temperatures affect the process [90]. The belt, which ensures the continuous transfer, is made of materials such as Polytetrafluorethylene (PTFE) to avoid sticking of the molten polymer on the belt [90]. MonoPan® sandwich panels (Figure 13) are produced by the double-belt laminating process by Wihag Composites GmbH, Germany [54,55]. MonoPan® sandwiches consist of PP glass fibre composite skins and a PP honeycomb core. With a production speed of 4 metres per minute large panels boasting a width of up to 3 metres can be manufactured continuously.

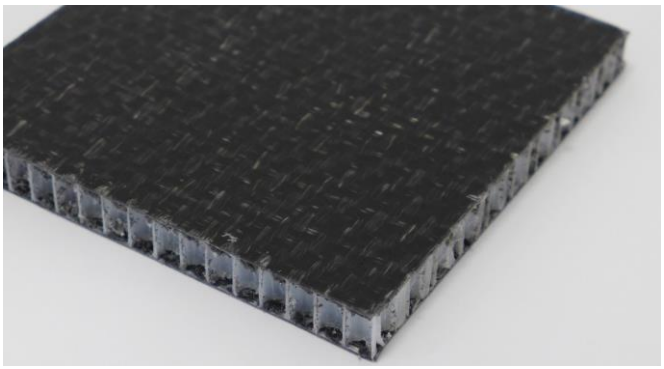


Figure 13: MonoPan® Panel

Fan et al. [90] developed a heat conduction model for the continuous production of TPC sandwich with a honeycomb core by means of a double-belt laminator. Besides the theoretically generated information, he produced 600 mm wide panels with a height of 8 mm. The skins as well as the honeycomb core were made from PP. The heating temperature of the laminator was set to 210 °C. The sandwich panel underwent a heating period of 8 seconds to heat the top of the honeycomb core through the skins up to 165 °C, followed by a 12 second lasting cooling period at a production speed of 5 metres per minutes.

Mayer et al. [62] developed a high-speed manufacturing method based on double-belt laminating for the production of TPC sandwich systems. Semi-finished glass fibre reinforced Polyamide 6 (PA6) laminates are stacked with a 3D mesh of a glass fibre PA6 co-knitted core and consolidated by using a double-belt press to an intermediate product. The knitted core is thereby maximally compressed. Both core and skins are completely impregnated with the thermoplastic material at a temperature above the melting point of PA6 and a pressure of more than 5 bar. In a second step, the intermediate product is heated again above the melting point of the thermoplastic matrix which leads to a self-expansion of the core to its original thickness. The self-expansion is caused by the release of internal stress stored in the threads during the compression and consolidation [62].

Isosport Verbundteile GmbH [121] describes in a patent the manufacturing process of a PP based thermoplastic laminate by double-belt laminating. In a first step, two non-woven fabrics are pulled through an extrusion die while being impregnated with molten PP. Simultaneously a PP based foam core is transported through a hot air jet. Then the hot and impregnated non-woven fabrics are stacked on both sides on the core and the set-up is transported into a double-belt press. The sandwich is consolidated under pressure and cooled down during the continuous transport through the press.

Giehl [122] reports on a semi-continuous press process, which enables the production of TPC sandwiches of different shapes in one step. A semi continuous press was therefore installed at the Institut für Verbundwerkstoffe GmbH at the University of Kaiserslautern, Germany. It is a combination of two press sections, which can cooperate or work individually.

2.3.4 In-situ foaming

Another process to achieve a skin-to-core fusion bond for TPC sandwiches is in-situ foaming, where foam is developed during the manufacturing process. Compared to other TPC sandwich manufacturing processes, the production of the core occurs simultaneously to the bonding of the core to the skins [76]. As the name indicates, this method only works for foam structures. Different methods exist to foam in-situ [76,123,124]. One process makes use of a thermoplastic film which is soaked with a blowing agent. The film is stacked with the thermoplastic composite skins and transferred to a press. The press closes and heat and pressure are applied. Fusion bonding between skins and film, which will later become the foam, is achieved. The solvent contained in the film improves the fusion bond by dissolving or softening the inner surface of the skins [75]. The heat additionally activates the blowing agent and the foam starts to expand, see Figure 14. The press must open slightly to define the thickness and the density of the foam. By cooling the sandwich, the structure becomes solid and a bond between foam and skins has developed [75,76,125,126]. The film foaming process depends on several parameters, which are partly interrelated. On the one hand, the process

is affected by material parameters such as type of blowing agent, amount of polymer and blowing agent as well as type of skins. On the other hand, the properties of the final product can be controlled by choice of temperature, pressure, heating time, opening speed and opening height of the mould and the cooling rate [76]. Schreiner Luchtvaart Groep B.V. applied for a patent [127] for PEI and PES based sandwich structures, which refers to the in-situ foaming method. Brouwer [75] reported on the production of PEI based sandwiches.

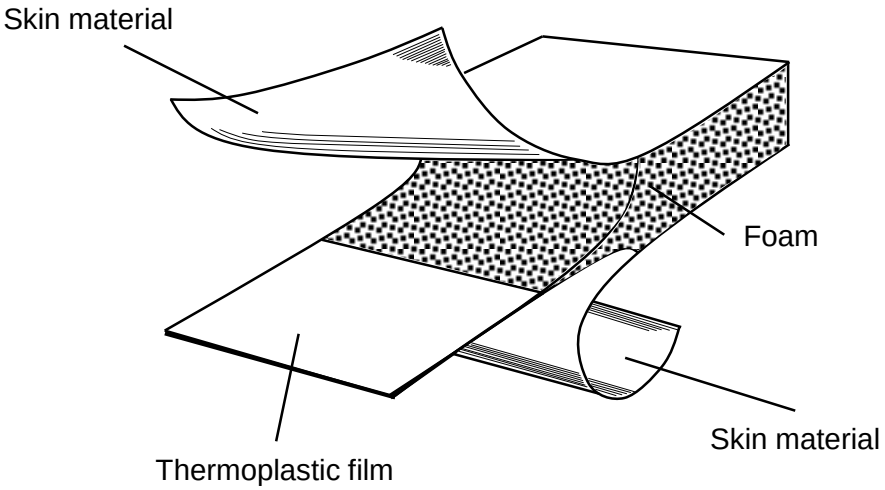


Figure 14: Principle of film foaming method according to Beukers [125]

In a first step so called pre-compacted PEI fibre reinforced laminates and a PEI film containing Methylene Chloride (MC) are produced in a press at high temperatures. A first linkage between the fibre reinforced laminate and the thermoplastic film is realised. In a following step the pre-compacted laminate is exposed to heat, which leads to de-compacting. This step is conducted in a press again. Film foaming starts within seconds and the press opens to allow expansion of the film. In the case of a PEI film loaded with 17 % MC, a foaming temperature of 175 °C is suitable. The thermoplastic film is able to expand to approximately 16 times its original volume. Upon reaching the desired thickness, the opening of the press is stopped and the sandwich is cooled down. Additionally, the sandwich has to be dried afterwards to remove any remaining solvents. The PEI based sandwich specimens feature a tensile strength of 3.8 N/mm. Provo Kluit further developed the film foaming process in [76] by improving the process parameters, such as the cooling rate. Additionally, he investigated the application of other blowing agents such as Acetone. Film foamed panels, mostly based on PEI, were manufactured and distributed by the company FITS Technology (Driebergen, The Netherlands). The sandwich panels feature a compression strength of up to 3.5 MPa, a shear strength of up to 1.5 MPa and a tensile strength of up to 5 MPa. Furthermore, the sandwhich panels feature a climbing drum peel strength of up to 125 N.mm/mm [78]. Seven worldwide patents such as [126,128] protect the sandwich panels as well as the manufacturing methods. Today, the company SMTC (Boufféré Cedex, France) distributes the film foamed panels under the trade name DYNATECH®.

Thermoplastic films soaked with solvents/blowing agents can also be used for the manufacturing of sandwich structures without taking advantage of the foaming characteristic [75]. Placing the solvent loaded thermoplastic film in between skin and core structures made

of the same polymer, the solvent vaporises out of the film and dissolves the inside of the skin surface as well as the core surface leading to a fusion bonding between skin, film and core [75]. Additional heating of the setup speeds up the bonding process. Since only the skin and core surface are dissolved, the method is suitable for sandwich structures. Additionally, the loaded thermoplastic film offers the advantage of being expandable, which improves the joining of surfaces with large tolerances and roughness. Beukers [129] presented a sandwich structure with a honeycomb and an in-situ foam core combination. A thermoplastic foaming film is used to combine skins and honeycomb core. The honeycomb core features high specific strength and stiffness whereas the in-situ foamed core ensures a continuous bond to the skins with a filling character.

Another in-situ foaming method is injection foaming, also referred to as the TSG-method (Thermoplast-Schaumspritzgießen) [86]. The core polymer and blowing agent are separately mixed in a batch. The skins are positioned in a mould. Then the foam is injected at a pressure of approximately 20 bar in between the skins [93]. In doing so, a fusion bond between foam and skins is realised and the sandwich is consolidated in-situ [93,123]. Zepf [93] presented a PA12 based composite sandwich produced by injection moulding. The PA12 core featured a density of 0.5 g/cm^3.

Roch et al. [130] conducted investigations concerning injection moulded PP based composite sandwiches. The skins were manufactured out of unidirectional orientated glass fibre/PP tapes, which were automatically placed and consolidated by vacuum or compression moulding. In the following step (step A in Figure 15) the two consolidated laminates, which function as skins, were fixed in the mould cavity. To allow fusion bonding to the core, the surfaces of the skins were heated indirectly, see step B in Figure 15. Next, the mould was closed as quickly as possible in order to minimise heat loss, followed by injection of the gas-loaded PP melt, see step C in Figure 15. After filling of the cavity had been completed, a pressure drop was created by expansion of the mould, which led to foaming of the core, see step D in Figure 15. The sandwich dimensions were controlled by the expansion of the mould. After cooling, the sandwich was released, see step E in Figure 15. Sandwiches with a total height of 6.4 mm and skin thickness of 0.26 mm as well as 1 mm were realised.

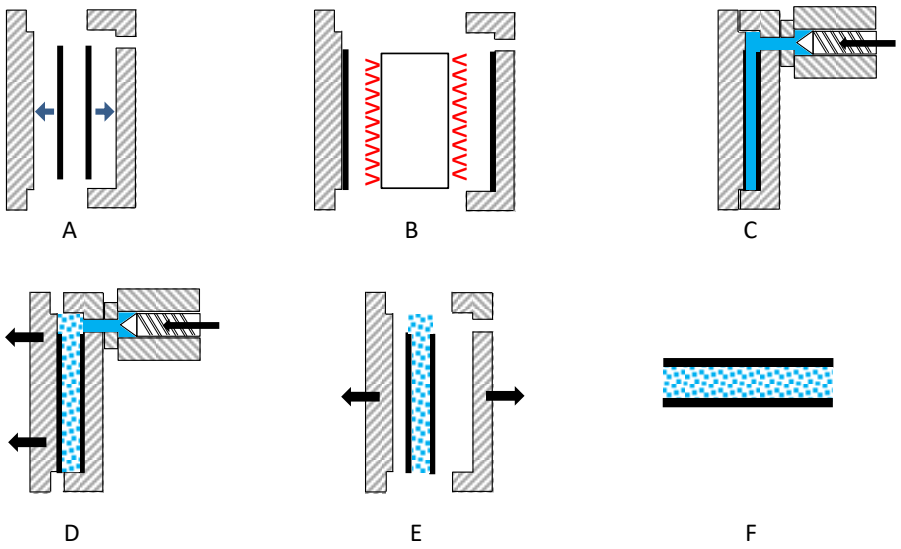


Figure 15: Manufacturing steps of injection foaming according to Roch et al. [131]

Another approach which should be mentioned briefly is the combination of injection moulding compounding (IMC) and foam injection moulding (FIM). Long glass fibres and a thermoplastic melt such as PP, loaded with a blowing agent such Nitrogen (N_2), are injected into a mould. The foam is compacted at the outer area, in contrast to the centre, where a lower density structure is realised. The result is an in-situ produced integral foam, which has similar characteristics to a thermoplastic composite sandwich based on the density gradient [123,131].

In 2014, novel PET or Polybutylene terephthalate (PBT) thermoplastic particle foams, which show high impact resistance or form-stability at high temperatures were introduced to continue the successful history of particle foams, which started with the development of the particle foam Styropor® by BASF SE 60 years ago [86,124]. Today, expanded PP particle foams, named EPP, are often applied in automotive interior parts. Particle foams are produced by micro-granulate, loaded with a blowing agent, which is foamed to foam pearls (particles) in a first step. Further processing to the final part is then conducted in five steps: The foam pearls are introduced into the cavity of the tool under pressure (1.5 bar – 4 bar) and compressed. The amount of pressure influences the resulting density. In the next step the cavity is vented by means of steam. Subsequently, the steam leads to softening of the polymers at the foam pearl surface with the result that fusion bonding between neighbouring pearls takes place [124]. The steam temperature during processing plays an important role, since the pearls are only meant to be softened at the surface, while the rest shall stay cool, which is needed for the stabilisation of the particles. Finally, cooling is conducted and the part can be released [124]. In combination with TPC skins, consisting of the same polymer used for the particle foam, a TPC sandwich can be realised in just one manufacturing step [124].

2.4 MECHANICAL PERFORMANCE AND SANDWICH TESTING

In the previous chapters, several research activities as well as developed sandwich structures are presented. Besides the development, sandwich structures have been mechanically and optically characterised in order to evaluate the mechanical performance of skins and core, the skin-to-core bonding strength, as well as the properties of the sandwich as a whole. The sandwich structures have been mechanically characterised by several testing standards:

- Tensile testing (ASTM C279 [39,57,67,76,78,90], DIN EN ISO 5624 [80])
- Peel testing (ASTM D1781 [50,78], EN 2243-3 [106], VDI 2019 [80])
- Flexural testing (ASTM C393 [39,46,50,67,80], AITM 1.0018 [106], BS EN 2746 [40])
- Shear testing (ASTM C273 [39,67,76,77])
- Compression testing (ASTM C365 [76,77], ASTM D1621 [90])
- Interfacial fracture testing (DCB after ASTM D5528 [67], SCB [81])
- Impact testing (ASTM D3763 [49])

However, due to different applied sandwich geometries such as skin and core thickness, length and width but as well as due to the different testing standards, a comparison of the mechanical performances of the presented structures is not possible.

2.5 MANUFACTURING OF 3D SANDWICHES

Until now only processes for the manufacturing of 2D TPC sandwich panels have been discussed. Several researches mentioned that the process window for fusion bonding of skins and core is narrow, since it is limited on the one hand by a weak interfacial bond at lower temperatures and on the other by core collapse and skin de-consolidation at higher temperatures. Another point of complexity is added when 3D sandwich structures need to be created, for which, the temperature and pressure distribution is more difficult to control. This section presents efforts as described in the public literature to realise 3D TPC sandwich structures. For manufacturing 3D sandwich structures, the mechanisms responsible for skin-to-core bonding are the same as for 2D sandwich structures [22]. Lightly curved panels may even be manufactured in a similar way to flat panels with the use of a shaped mould. More complex geometries may require shaping of the core to near net-shape prior to the application of the skins, which for example can be realised by machining, thermoforming or expansion to the desired shape [22]. The more complex the curvature, the greater the need for additional pre-forming of the skins [22].

2.5.1 One-step (direct) manufacturing of 3D TPC sandwiches

In the literature, a few investigations on simultaneous (direct) forming and joining of 3D sandwich structures applying compression moulding or in-situ foaming are reported [47,65,69,91,132]. For example, Reynolds et al. [65] applied non-isothermal compression moulding for manufacturing PP based composite sandwich structures. Besides investigations on flat panels, he also studied one-step manufacturing of slightly curved 3D sandwich beams featuring a 4000 mm radius. Renault [47] reported on thermoforming of the Sandwiform®-panel, consisting of PP composites and a PP honeycomb core, while simultaneously consolidating it in a press. Core and skins are stacked, heated in an IR-field and then formed and joined in a single step during moulding. Sandwich structures with a complex shape can be realised in cycle times of about 1 minute and pressure as low as 10 bar with this process. Breuer et al. [69] applied the compression moulding process for manufacturing GF/PA12 and PA12 honeycomb core and PMI foam core 3D sandwiches. The components were stacked and heated by contact heating and transferred into the press. A hemispherical mould was used to shape the sandwich. To facilitate the forming of the sandwich, a vacuum was applied in the negative mould. The process temperature was identified to be in the range of 185 °C – 210 °C.

Henning et al. [132] reported on a direct compression moulding process of 3D thermoplastic composite sandwiches. The core was extruded directly between the heated outer layers, followed by a forming and consolidation process. The skins were based on glass fibre reinforced PP, while the core consisted of recycled glass mat thermoplastic (GMT) or long fibre thermoplastic (LFT) materials.

Nowacki [64] described direct compression moulding of 3D sandwich in the shape of a seat shell for the automotive industry. In order to meet the suitable process window for forming skin and core, while simultaneously ensuring a bond between skin and core, the temperature is recorded for the skins, the core surface and the core centre by thermocouples. However, due to the application of different materials (GF/PP for the skins and PEI foams as the core), where the core is not softened, the process is simplified in comparison to a one polymer sandwich, but a fusion bond between skins and core cannot be achieved.

The in-situ foaming methods (film foaming and injection foaming) can also be suitable for the production of 3D sandwich structures [91]. Since the internal pressure during the foaming process can reach up to 10 bar for film foaming and up to 20 bar for injection foaming, the skin sheets can be formed using this pressure into a mould, and a 3D sandwich realised in one step. Nevertheless, the skins can be formed in a previous step as well. Thermoplastic particle foams can be easily introduced into a 3D mould with previously shaped skins.

2.5.2 Two-step manufacturing of 3D TPC Sandwiches

Thermoforming of initially assembled flat sandwich structures is another method of realising 3D sandwich parts. Although it is an additional step, it can be an effective way to obtain complex sandwich structures [71]. The thermoplastic composite skins and the thermoplastic core are heated up to the softening temperature of the polymers, followed by a stamping step in a cold or tempered mould. Phenomena such as skin de-consolidation during heating, or core collapse due to high pressure and temperatures are nonetheless challenges in using the process [71]. For a sandwich, based on the same thermoplastic polymer in core and skins, the process window (temperature and pressure) for thermoforming skins and core can be illustrated as in Figure 16 [71]. Figure 16 shows that the process window varies for skins and core in terms of temperature and pressure. The core needs to be heated to such an extent (lower temperature limit) that it allows forming without destroying the cell structure (foam tearing) or causing internal stress after cooling. However, the core must not melt (upper temperature limit) in order to prevent the core from collapsing and to maintain a sufficient form- or compression-stability to enable precise shaping [71].

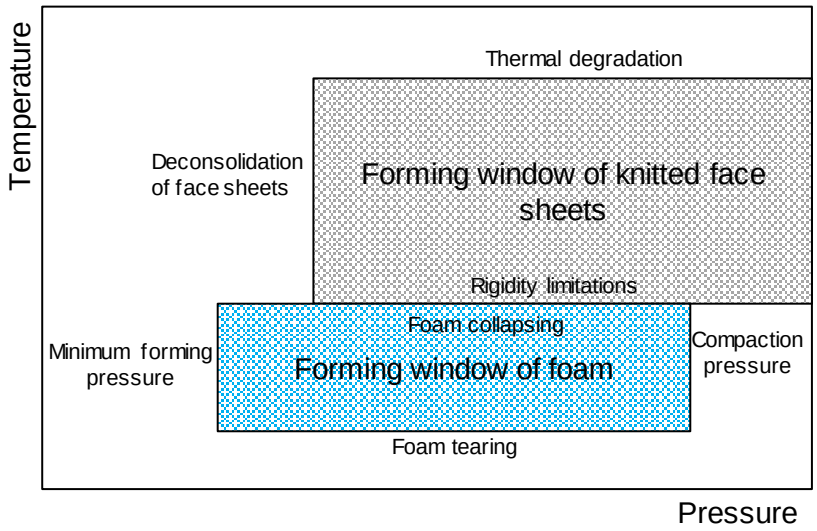


Figure 16: Schematic processing window for thermoforming a TPC sandwich based on a single polymer in skins and core according to Rozant et al. [71]

Some amorphous thermoplastic cores offer suitable characteristics for thermoforming. Due to their amorphous structure they feature a broad softening temperature range and only lose their complete form-stability at very high temperatures [91]. The pressure limits for the core are set on the one hand by an insufficient forming pressure (lower pressure limit) and on the other by a pressure which causes core compaction (upper pressure limit) since it exceeds the compression strength of the core. Forming of thermoplastic composite skins requires sufficient

heating due to the rigidity limitations of the materials (lower temperature limit) while the upper temperature limit is given by extensive heating which leads to material degradation. Heating the laminates above the softening temperature of the skin matrix polymer may lead to de-consolidation of the skins caused by the release of elastic energy stored in the skins during consolidation, which can be prevented by supplying sufficient pressure (lower pressure level) [71]. An upper pressure level for the skins may be given by matrix material squeeze out or fabric deformation, though it is not mentioned in [71].

Rozant et al. [71,73] studied the forming behaviour of PEI based sandwich materials, which included the drapeability of skin materials. Glass fibre double warp-knitted bar knits were selected for the reinforcement since they feature high drapeability, low forming energy and quasi-isotropic behaviour. PEI foams (Airex® R.82.80, Airex AG, Switzerland) were used as the core. Skins and core were adhesively bonded with an epoxy film before being thermoformed in a following step. By investigating the mechanical behaviour relative to the temperature of the PEI core and the PEI sandwiches separately, the optimal process window was defined. A processing temperature of 165 °C – 185 °C seems to be optimal for the core, whereas the skins need to be heated up to above 280 °C. A forming pressure range between 0.03 MPa and 0.11 MPa seems to be suitable for both parts. In order to fulfil the temperature process window, a strong thermal gradient must be created between the skins and the core. By applying thermal simulations, a two-step heat conduction setup was developed. In the first step, the temperature of the whole sandwich structure was elevated between two hot plates. In the following step, a fast heating of the skins was conducted before the sandwich was transported into the mould for shaping. The results showed that a PEI based sandwich could be shaped successfully into a hemispherical-ellipsoidal shape in less than 7 min.

Beukers [125] presented thermoforming technologies for in-situ foamed PEI sandwiches. A production machine was developed for edge forming of the sandwiches, see Figure 17. This machine consists of four individual adjustable stamps. Two stamps function as deformation stamps, and two as consolidation stamps. The sandwich panel is transferred into the machine first, see step 1 in Figure 17. In a second step, the deformation stamps that are heated up to temperatures of 320 °C (upper stamp) and 150 °C (lower stamp) close resulting in edge forming. In the following step (step 3 in Figure 17) the sandwich is transferred to the consolidation stamps which ensure a full forming and consolidation of the pre-formed edge of step two. The result is a sandwich panel with formed edges.

Another method presented by Beukers [129] is the folding process. A pre-heated die penetrates a sandwich halfway at the spot where the folding is to take place. The die has a wedge-shaped form, which produces a groove and ensures pre-folding of the panel. In a following step the shanks of the sandwich are folded around the groove. Since the pre-heated die softens the sandwich skin in the area of the groove, the sandwich skin can be fusion bonded again in the bent corner.

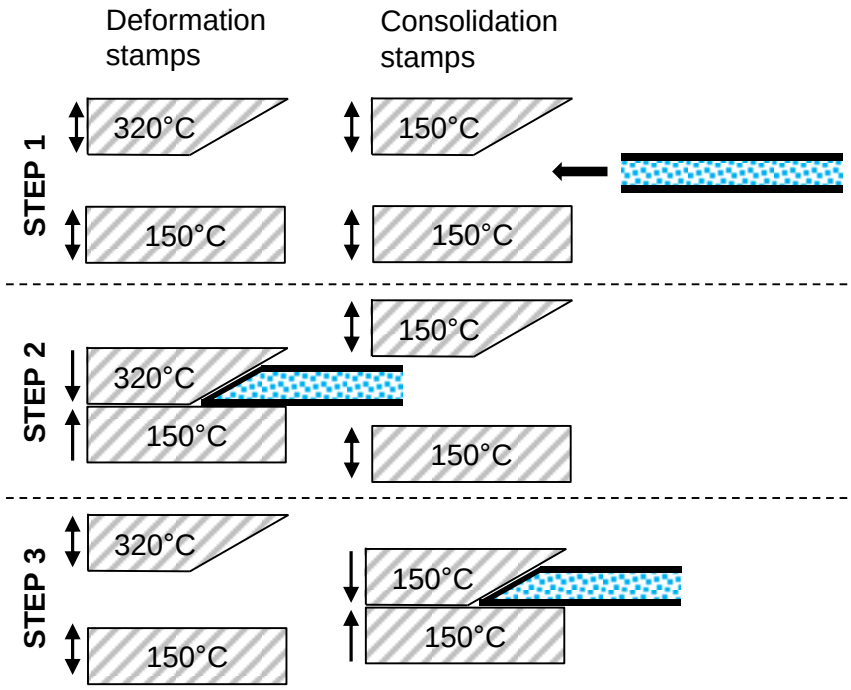


Figure 17: Principle of edge forming according to Beukers [125]

Another thermofolding approach is presented by Offringa [37]. Heat is locally applied at one sandwich skin by a heated knife, where a fold line is created. During folding, the heated skin is pressed into the sandwich panel and a butt weld at the inner radius of the sandwich is obtained, see Figure 18. A strong edge is created, even though the weld is not fibre reinforced.

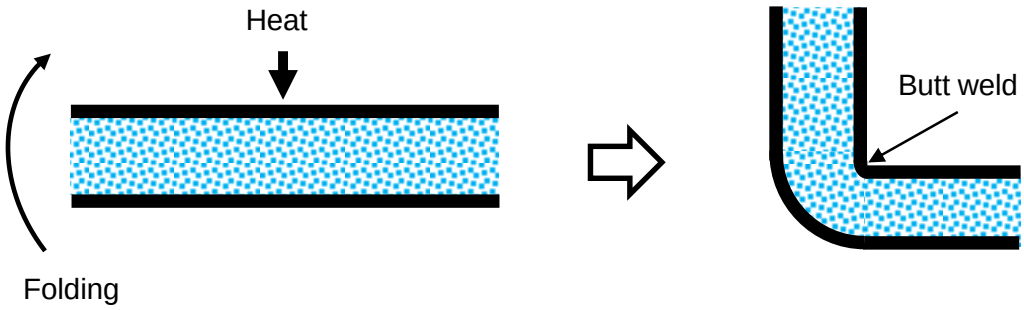


Figure 18: Thermofolding of TPC sandwiches according to Offringa [37]

One last point that needs to be highlighted is the deformation of the core during 3D sandwich manufacturing. L. Sorrentino et al. [133] investigated the thermoforming behaviour of PET foam cores. A mould with a 90° forming angle was designed for planar deformations (L-shape) of the foams. The samples were heated for 10 minutes at the intended temperature (> 160 °C) and then thermoformed by pressing them into the mould by means of a cold indenter. The tests were performed in order to define the minimum thermoforming temperature and to investigate the effect of deformation on cellular morphology. PET foams were successfully thermoformed at temperatures above 160 °C (85 °C higher than T_g). However, many samples showed a spring back effect due to residual strain stresses caused by the high crystallinity of the PET material applied. Moreover, the formed foams featured a cell aspect ratio gradient

which induces a variation in the cell morphology through the thickness, which was more pronounced for higher temperatures. Compared to an undeformed foam (cell aspect ratio ~ 1), the centre cells were compressed (aspect ratio ≥ 1), while the outer cells were stretched (aspect ratio ≤ 1).

2.6 MODELLING OF SANDWICH PRODUCTION

The key for producing thermoplastic composite sandwich structures is the right selection of relevant processing parameters such as heating temperature, pressure, etc. The process window can be determined by experimental investigations, as presented in the previous sections. Modelling is another approach. It helps to understand the influence of the parameters and materials. In the past, some models have been developed to support the manufacturing of thermoplastic sandwiches, which will be briefly presented in the following section.

2.6.1 Heat transfer

Heat transfer is an important phenomenon for a thorough understanding of the manufacturing of thermoplastic composite sandwiches [22]. During fusion bonding of composite skins and core, the interface temperature is critical for the bond [68]. To avoid core collapse, the core in general has to be kept below the softening temperature, while the surface of the core and skins must be in the molten state to allow interdiffusion of molecules [22,68]. Applying the non-isothermal compression moulding method, the skins are heated above the melting temperature before being placed on the cold core and consolidated under pressure. To find the right heating temperature, the temperature evolution within the laminates, interface and core is of great interest. To this end, Trende et al. [68] worked out a heat transfer model to predict the temperature evolution during fusion bonding. They applied a 1D heat transfer and crystallisation model for heating and cooling of glass fibre reinforced PA12 laminates and for the assembly of the PA12 composites skins and a PMI core. PMI was chosen for the core. Although not being a thermoplastic material, it simplifies the modelling and presents an adequate system. Later the model was extended to a 3D model, implemented in a finite element program. The simulations were compared with experimental data. Although difficulties such as the determination of the thermal contact conductivity between skin and core occurred, they showed that it is possible to obtain good relation between predicted and experiential obtained data.

Passaro et al. [89] used one-dimensional (1D) finite element analysis to simulate thermal conduction through the stacked layers and the core during non-isothermal compression moulding. The modelling was designed to calculate temperatures at the skin-to-core interface and in the middle plane of the core. The predictive analysis was essential to choosing parameters which ensured the melting of the PP in the interface and to avoiding core collapse as a result of too extensive heating. Figure 19 shows typical temperature curves obtained with simulations and experimental data. The graph refers to a sandwich with PP composite skins and a PP honeycomb core. During processing the skins were heated to the melting temperature (approx. 200 °C) and then combined with the cold plates and core.

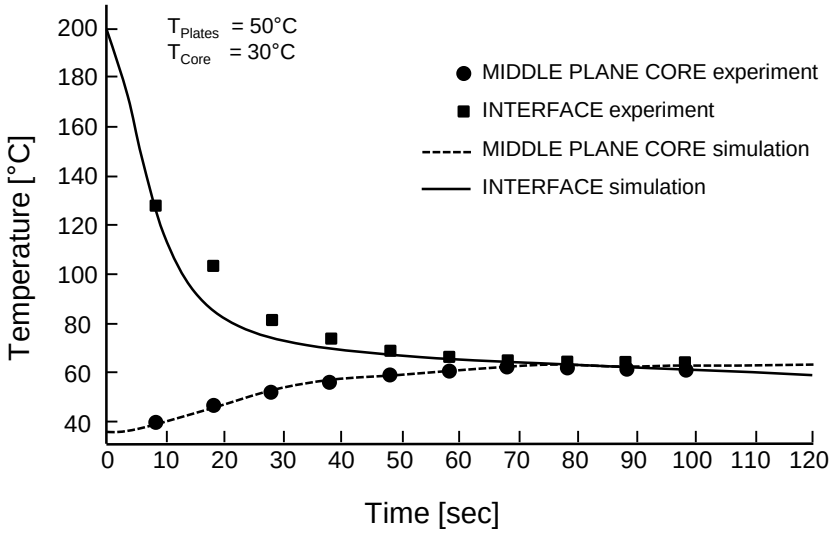


Figure 19: Temperature history during non-isothermal compression moulding according to Passaro et al. [89]

Fan et al. [90] developed a 1D heat transfer approach for modelling the heat conduction during fusion bonding of thermoplastic skins to a honeycomb core by double belt laminating. Three entities, namely heating/cooling elements, a PTFE belt and the homogenised honeycomb sandwich were considered for the model. The 1D heat transfer equation was solved by means of the finite difference approximation and boundary conditions such as Dirichlet and Robbins conditions. By means of in-situ temperature measurements, the model was subsequently verified. PP based skins and a PP honeycomb core were fed into the double belt laminator. Thermocouples were positioned between the heating/cooling elements and belt, between belt and sandwich panel and at the centre of the honeycomb core to record the temperature history during processing. Fan et al. [90] was able to show that the model approach is valid for the heating stage, though they obtained no good agreement with the measured results during cooling. The deviations between measured and predicted temperature development during cooling are related to the complexity of the cooling tool, which cannot be accurately implemented in the model.

Rozant et al. [72,73] investigated the thermoforming process of PEI based sandwiches. He developed a two-stage heating process to enable the optimal forming conditions for skins and core. Additionally, a finite element thermal model was worked out to simulate the temperature profiles in the sandwich during heating. By using an inverse method, the thermal properties and the boundary conditions were determined.

2.6.2 Face to core bond

A good level of bonding between composite skin and core is important for the unrestricted performance of the sandwich. The interface should feature a mechanical performance which is at least comparable to the mechanical performance of the constituents [6,22]. Therefore, it is relevant to understand the bond strength by modelling the process as a function of materials and processing conditions.

Akermo and Aström report [6,52,53] on a bonding model for thermoplastic honeycomb sandwiches. The model assumes that the edges of the cell walls of the core are melted by the

heat of the pre-heated skins. This enables intimate contact between skins and core walls, so that molecular diffusion across the interface can take place. The bonding model considers several submodels such as a heat transfer submodel, a contact submodel and a bonding submodel [6]. The heat transfer model was described by a 1D heat conduction equation. The contact submodel considers the deformation of the cell walls, which melt during the consolidation process. As a result, the bonding area is increased. The bonding submodel refers to the 'autohesion' theory, which suggests that bonding occurs when the molecules near the surface become mobile and the bond strength develops through a combination of surface rearrangement, wetting, diffusion and randomisation. These steps depend on processing conditions such as temperature and compression time. Describing the diffusion takes the reptation model of molecules by de Gennes [134] into account. Akermo and Aström [6,52,53] transform all these submodels into one expression, as in reality these phenomena occur at the same time. The resulting degree of bonding is the sum of the products of contact surface and degree of non-isothermal bonding. The key parameters determining the final bond strength are thereby the temperature during processing, pressure and overall processing time. In combination with the material properties these parameters enable modelling of all submodels which contribute to the final degree of bonding. The modelling was verified by experimental trials [53].

Akermo and Aström additionally presented in [70] a model to predict the bond strength between thermoplastic skins and a rigid, closed cell foam core. The approach is based on the assumption that the bond strength is to some extent proportional to the amount of resin that flows during consolidation into the open cells of the core to bond the constituents by mechanical interlocking. Therefore, the matrix flow at the skin-to-core interface has been modelled with the intention of determining the influence of the processing parameters and material properties on the penetration depth of the matrix flow into the core. Akermo and Aström provided an expression for the matrix penetration depth depending on the matrix flow into the surface cell, the gas permeation and the gas pressure in open cells. The model was applied to a numerical example. Glass fibre reinforced PA12 skins and a PMI foam core were taken as materials. Additionally, results of the numerical approach were compared to an experimental study of compression moulding of glass fibre/PA12 skins and a PMI core. The results of the numerical approach showed that matrix penetration depth increase with increasing pressure up to about 1 MPa. This approach also shows that matrix penetration depth decreases with increasing skin temperature due to the increasing gas pressure within the core cells. According to the assumption that the bond strength is proportional to the matrix penetration depths, the model predicts that a high bond strength can be obtained by applying as high a pressure as the core can sustain at lowest possible temperature. The prediction could be partly substantiated by the experimental results.

2.6.3 Forming models

Möller et al. [135,136] proposed mathematical approaches for describing material behaviour for simulations of the forming process of thermoplastic sandwich structures. In particular, the mathematical description of mechanical behaviour of the fabric reinforced thermoplastic composites is based on a separate consideration of the behaviour of matrix material and the reinforcing fibres and the additional overlap of both contributions. The mathematical approach for the description of the behaviour of the foam is based on decomposition of the foam into two

parts. The foam is considered a parallel connection of a skeleton and a nonlinear elastic continuum. The material models were verified by experimental results of a forming process of sandwich panels in spherical geometries.

Besides the heat-transfer model (refer section 2.6.1), Rozant et al. [72,74] also suggested a finite element approach to simulating the forming behaviour of PEI based sandwich panels. The skins were modelled by using shell elements while the foam core was described by volume elements. By means of mechanically testing the skins and core at high temperatures a bilinear isotropic material model for the sandwiches was implemented. For thermoforming experiments, initially flat preforms were pressed into a mould with double constant curvature. The forming model was validated by the experimental displacements of the shaped parts. The displacements were measured by a Moiré technique. The forming predictions showed good qualitative (shape) and quantitative (values of displacements) agreements compared to the experimental approach.

Maculuso et al. [91] performed a deep drawing finite element approach to PP based sandwiches with a honeycomb core. First, the influence of the out-of plane core shear strength on the minimum forming radius of the tool was investigated. For a PP honeycomb sandwich with a core cell size of 6.4 mm, wall thickness of 0.16 mm, core thickness of 7.3 mm and skin thickness of 0.8 mm the out-of-plane shear behaviour was modelled by using ABAQUS. With calculated core shear strength of 0.8 MPa, the minimal allowed tool radius was identified to be 77 mm. Based on these investigations a deep drawing simulation with bending in one direction and in two directions was conducted.

2.7 CONCLUSION

The application of thermoplastic composite skins and thermoplastic core materials for sandwich structures is advantageous due to material properties, minimised production cycle times and environmental sustainability. To achieve a sandwich structure of sufficient quality, the thermoplastic composite skins and thermoplastic core should be properly joined. Several different methods for skin-to-core joining are described in public literature. The processes for skin-core joining can be divided into two main groups: adhesive bonding and fusion bonding. Using a supplementary material to join skins and core is considered an adhesive joining technique and has the advantage of the structure of the constituents not really being affected while joining. However, adhesive bonding of skins and core is generally considered time and labour intensive and furthermore often created a weak skin-to-core bond. Another method of joining thermoplastic skins and core is fusion bonding, which is based on molecular exchange across the interface. By fusion bonding skins and core together, the interface can approach the bulk properties of the adherents. Moreover, fusion bonding can be performed in short cycle times.

Different methods such as vacuum moulding, compression moulding and double-belt laminating make use of heat to soften the polymers and pressure to fusion bond the core and skins. A critical point for fusion bonding is the definition of the process window for the production of a well consolidated sandwich, since it is limited on the one hand by a weak interfacial bond at lower temperatures and on the other by core collapse or compaction and skin de-consolidation at higher temperatures. These phenomena depend on the properties of the polymers such as softening temperature (glass transition temperature or melting

temperature) and the rheological behaviour. Therefore, care needs to be taken by the choice of processing conditions.

To date, most manufacturing processes have primarily focused on the production of 2D sandwich structures. Manufacturing of curved 3D sandwiches poses even more challenge. Therefore, most thermoplastic sandwich structures are being formed in a separate step, where heat is applied in a controlled manner on the 2D sandwich structure before formed. Since simultaneous forming and consolidation of the TPC sandwich seems most economical, the direct forming process of 3D sandwich structures requires more investigation.

Another method of producing thermoplastic composite sandwich structures can be realised by in-situ foaming methods such as film foaming, injection foaming or particle foams. The core is foamed during the process by the expansion of a thermoplastic material with the help of a blowing agent, injection of polymer foam or by stabilisation of particle foams by means of steam. Core collapse is not an issue here. In addition, the pressure produced during foaming can be used to shape the skins in one step. Therefore, these manufacturing methods look promising for the production of 3D sandwich structures. The film foaming method is already being successfully applied in PEI based sandwiches, particle foams or injection foaming for commodity polymer foams.

Furthermore, several researchers describe process models to understand the process governing mechanisms, and to narrow down the process window before conducting experimental trials.

3. GOAL AND APPROACH

3.1 GOAL

The motivation of this study as stated in chapter 1 is the development of a manufacturing process for sandwich structures in order to lower the manufacturing cost by reduced cycle times (< 4 hrs), minimise maintenance during service and improve the environmental footprint of sandwich structures. Thereby, it is pursued to develop a process based on thermoplastic skin materials and a thermoplastic foam core, which are both suitable for structural helicopter applications. To ensure the principle of function in these sandwich structures, a good bond between skins and core must be achieved. Thus, the skin-to-core joining process plays a key role during manufacturing. Furthermore, the skin-to-core joining process has a significant effect on processing times and manufacturing cost.

Analysis of state-of-the-art of thermoplastic sandwich processing reveals that fusion bonding of skins and core is an efficient way to realise a strong bond between skins and core in short cycle times (below three minutes [124]). Other joining techniques such as adhesive joining by epoxy based supplements do not show a significant cycle time reduction advantage in comparison to state-of-the-art Nomex® sandwiches. Several investigations on fusion bonding of thermoplastic skin and core materials have been performed in the past, and a few commercial sandwich structures realised by fusion bonding are available on the market. However, fusion bonding of skin and core materials suitable for structural helicopter applications has not been investigated yet. The investigated and available sandwich structures are either based on commodity or engineering polymers envisaged for automotive or packaging applications, which do not fulfil the high material requirements of helicopter structures, see requirements table in chapter 1. The applied sandwich materials cannot fulfil for example the required characteristics and performance at elevated temperatures above 135 °C and feature insufficient FST characteristics. In the case of high performance material applications such as PEI, which could withstand the high operational temperatures, sandwich structures are limited with regard to design freedom, for instance in the use of multi-ply skins, which leads to limited possible applications.

Furthermore, several researchers have noted various challenges such as core collapse, which occur during fusion bonding of skins and core, and have highlighted the importance of utilising appropriate process parameters in order to produce a sandwich of sufficient quality. Moreover, little experience exists on the production of formed sandwiches, since forming complicates processing requirements, and narrows the processing window even further.

This leads to the specific goals of this thesis:

- Selection of materials, which fulfil the requirements for helicopter applications (chapter 1) as well as a suitable manufacturing process.
- Investigations on the fusion bonding process of skin and core, in order to realise a good bond between skins and core. A good bond means that the skin-to-core bond does not represent the weakest link within the structure and is capable of transmitting shear and axial loads to and from the core. For that purpose, the process governing mechanisms shall be investigated in detail allowing the proposition of a manufacturing process

window. Furthermore, the influence of processing conditions on the skin-to-core bond quality as well as on the sandwich as a whole shall be characterised.

- Assessment of the mechanical performance of developed sandwich structures as well as production conditions by comparison to thermoset based state-of-the-art sandwich structures and according to aviation material requirements.
- Determination of process conditions for the realisation of formed panels as well as the proof of feasibility of a shaped demonstrator.

3.2 APPROACH

In order to achieve the above-mentioned goals, the approach pursued in this thesis is illustrated in Figure 20. Firstly, various requirements, deduced from different helicopter applications (refer chapter 1), serve as a guideline for the material selection (chapter 4.1). Based on analysis of state-of-the-art of thermoplastic sandwich manufacturing methods (refer chapter 2) and the chosen materials, compression moulding is selected as the manufacturing process (chapter 4.3), which is developed and adapted according to the ‘Thermabond’ process (joining processes for thermoplastic composites based on dual polymer bonding) to allow a process window (chapter 5). In chapter 5.5, the governing mechanisms of a fusion bond, namely ‘intimate contact’ and ‘healing’, are studied in detail and a theoretical model to predict the skin-to-core bond strength is proposed (chapter 5.5.1 to 5.6.4). Subsequently, the process is investigated experimentally and the model verified (chapter 5.7). The influence of processing conditions on the mechanical performance of the sandwich structures is characterised by several testing standards and presented in chapter 6. By using two reference thermoset-based sandwich structures and the requirements, the performance of the TPC sandwich structures as well as the manufacturing process is evaluated (chapter 7). The assessment of the sandwich structures shows the manufacturing potential but also the lower performance of the resulting sandwich structures. Therefore, a further development, particularly a method of modifying thermoplastic foam cores to improve the overall mechanical performance of developed sandwich structures, is presented (chapter 8). In chapter 9, the process window for manufacturing formed sandwiches is investigated and an approach based on a two-step compression moulding process is proposed and implemented. Finally, conclusions with respect to the goals are drawn and an outlook is given (chapter 10).

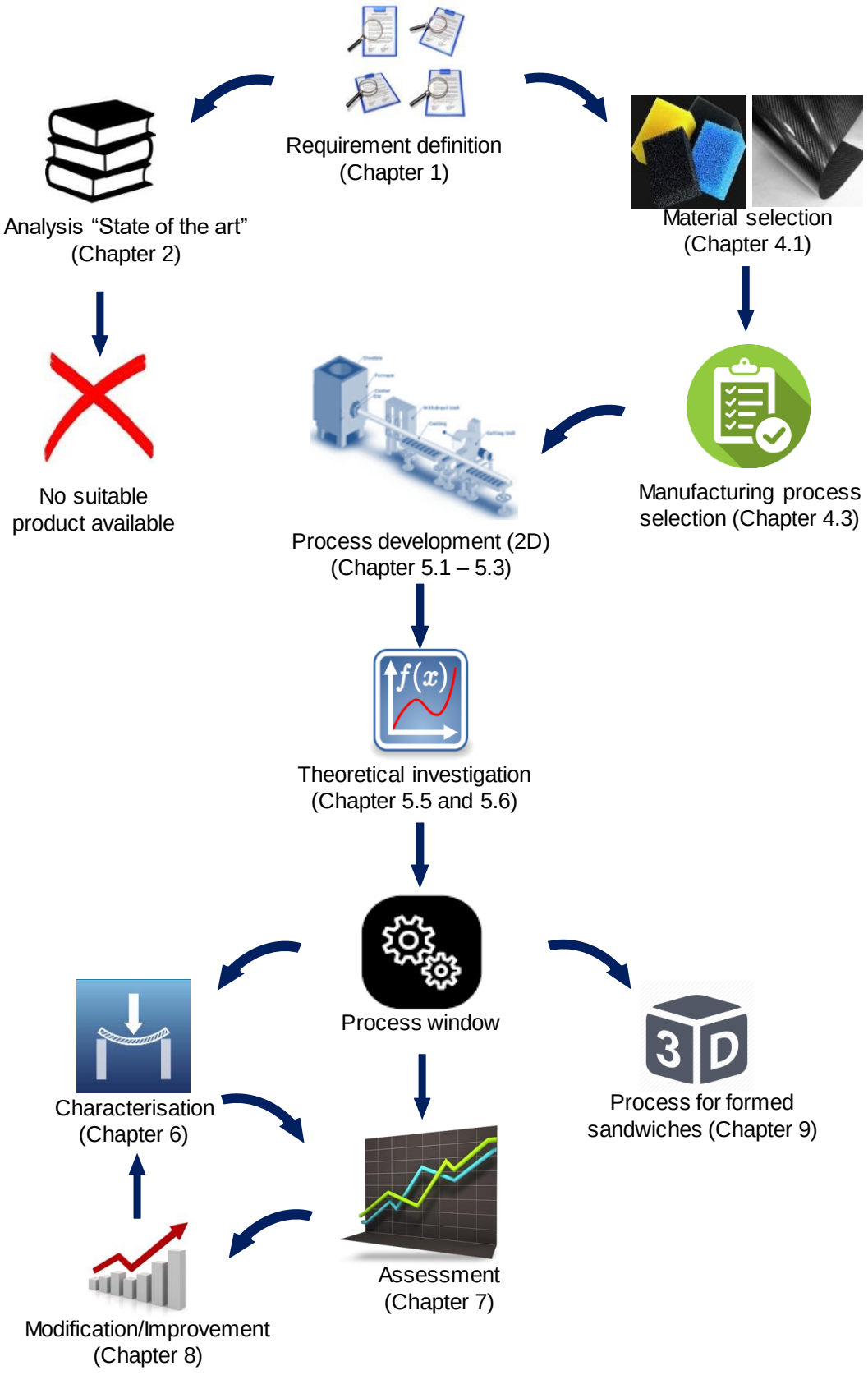


Figure 20: Schematic illustration of thesis approach

4. MATERIALS AND PROCESS SELECTION

4.1 MATERIALS SELECTION

Based on aviation material requirements, only high-performance polymers as defined in Figure 21 will be considered for skin and core components in the following study. In general, the aviation industry focuses on high performance materials due to stringent technical requirements aviation vehicles are subjected to, which becomes apparent by taking a look at applied materials in aviation vehicles today [137].

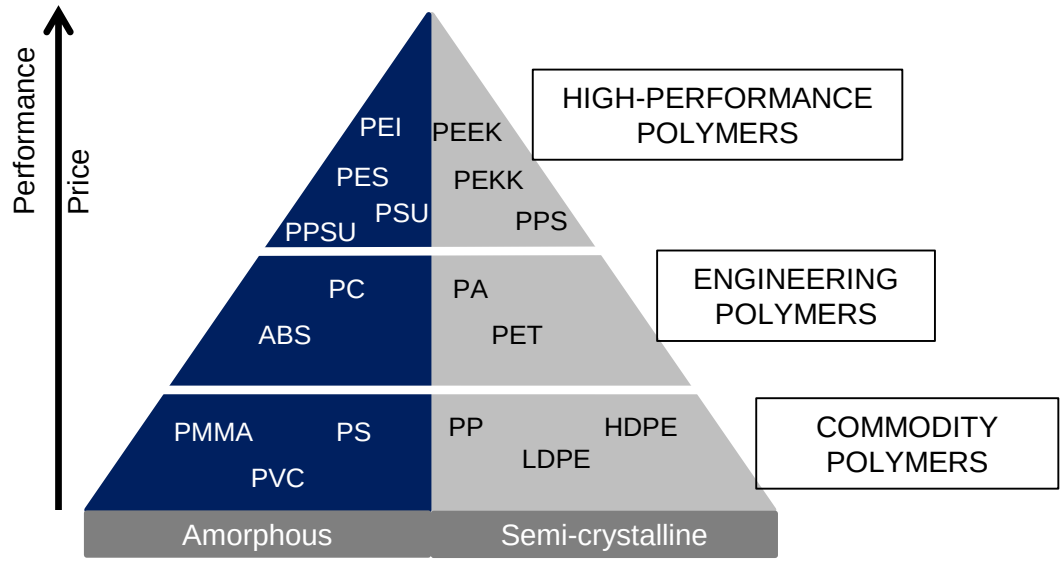


Figure 21: Polymer performance pyramid

4.1.1 Skin Materials

As mentioned in chapter 2, skins for thermoplastic composite (TPC) sandwiches consist of a fibre reinforcement and a polymer matrix system. Besides the selection of high performance polymers as the polymer matrix material, mostly carbon fibres are applied as reinforcement due the stringent requirements in the aviation industry for structural parts, and will be considered the only fibre reinforcement in this study. Carbon fibres exhibit the following high-performance properties.

- High strength to weight ratio
- High stiffness
- Chemical resistance
- Low thermal expansion

The production of thermoplastic composites, especially the impregnation of fibres with the polymer matrix, poses some challenges due to the high viscosity of thermoplastic polymers. Several TPC suppliers have specialised in the manufacturing of semi-finished fibre reinforced thermoplastic products, which are further processed to a final consolidated laminate in a separate step in-house or by other companies. Semi-finished thermoplastic products are available in the form of impregnated unidirectional tapes or textile fabrics.

In Table 5 several commercially available reinforced thermoplastic semi-finished products are presented. All semi-finished products are exclusively reinforced by carbon fibres. The matrix polymer, structure of the reinforcement, producing company and trade names are listed. These materials were evaluated in detail according to the requirements given in chapter 1 in Table 2. The evaluation showed that due to high requirements concerning chemical resistance, only semi-crystalline polymers can be utilised as skin material. Therefore, Polyetheretherketone (PEEK) and Polyphenylensulfide (PPS) based skin materials have been shortlisted for further evaluation. PEEK based materials are in general costlier compared to PPS based prepregs, but they feature slightly better properties such as a higher glass transition temperature (T_g) and melting temperature (T_m).

Table 5: Available prepreg materials with high-performance polymers as matrix material

Polymer	Structure	Company	Name
PEEK	UD	Tencate	Cetex® UD
PEEK	Fabric	Tencate	Cetex® RTL
PEEK	UD	Toho Tenax	Tenax®-E TPUD
PEEK	Fabric	Toho Tenax	Tenax®-E TPCL
PEEK	UD	Cytec (Solvay)	APC-2-PEEK
PEEK	UD	Suprem	Suprem™ T
PEEK	Fabric	Porcher	Pi preg®
PES	UD Tape	Suprem	Suprem™ T
PES	Fabric	Tencate	Cetex® RTL
PPS	UD	Tencate	Cetex® UD
PPS	Fabric	Tencate	Cetex® RTL
PPS	UD Tape	Suprem	Suprem™ T
PPS	UD	Ticona (Celanese)	Celstran® CFR-TP
PPS	Fabric	Porcher	Pi preg®
PPS	Fabric	Bond Laminates	Tepex® Dynalite
PEI	UD	Tencate	Cetex® UD
PEI	Fabric	Tencate	Cetex® RTL
PEI	UD Tape	Toho Tenax	Tenax®-E TPUD
PEI	Prepreg	Porcher	Pi preg®
PEKK	UD	Cytec (Solvay)	APC PEKK Prepreg
PEKK	Fabric	Tencate	Cetex® RTL

4.1.2 Core Materials

As reported in chapter 2, thermoplastic foam as well as honeycomb cores were applied in investigations published in literature. Furthermore, commercially available products based on thermoplastic honeycomb cores (Monopan®, Wihag-Composites) as well as foam cores (Dynatech®, SMTC) are available on the market. However, this study pursues to apply thermoplastic foams (chapter 1) since they offer several benefits in comparison to honeycomb cores:

- Isotropic properties
- Thermoformable
- Easier to shape by machining
- No telegraphing effect
- Less sealing and potting during manufacturing necessary
- Less water absorption
- Cost

As mentioned above, the focus concerning thermoplastic materials is very much on materials with high performance properties such as high thermal stability (T_g > 140 °C). On the market, a small assortment of high performance thermoplastic cores can be found. Polymer, trade name, structure and supplier of these high-performance thermoplastic cores are presented in Table 6.

Table 6: Available high-performance thermoplastic foam cores

Material	Name	Density range	Supplier
PEI	Ultem® foam	60 - 110 kg/m³	Sabic (US)
PEI	Airex® R82	60 - 110 kg/m^3	Airex AG (CH)
PPSU	Radel® Foam PXM	45 - 200 kg/m^3	Solvay (US)
PESU, PSU, PPSU	Ultratect® *		BASF (GER)
PES	Divinycell® F	40 - 130 kg/m²	Diab (SWE)

* Reported in literature, but no longer commercially available.

A detailed comparison of the aforementioned foam cores showed that they all feature similar mechanical properties at a comparable density level as well as high service temperatures and good FST (Fire, Smoke and Toxicity) properties. However, due to the fact that Polytherimide (PEI), Polythersulfone (PES) and Polyphenylsulfone (PPSU) are amorphous polymers, these foams have a drawback concerning chemical resistance against cleaning agents or solvents such as Methyethylketone (MEK) or Dichloremethane (DCM). However, the lack of chemical resistance would be acceptable if the core were to be fully covered by a skin, which has resistance against these chemical substrates.

4.1.3 Skin and core material selection – Miscibility of polymers

In order to realise a strong skin-to-core bond while keeping manufacturing cycle times short, the aim is to fusion bond skin and core materials, see chapter 2.2. Due to the fact that one specific high performance polymer does not exist and fulfil the requirements for composite prepregs for the skins and foam core structure, a hybrid combination has to be considered. The aim is therefore to cover the amorphous polymer based foam with semi-crystalline polymer based skins to ensure chemical resistance of the whole structure. This means that two chemically different polymers must be joined or mixed, which is often referred to as blending. Fusion bonding of two dissimilar polymers is no trivial task, since it requires the miscibility of the polymer pair [115]. Miscibility is here defined as the ability to form an indistinguishable homogenous phase [138]. However, most polymer combinations are not miscible or only miscible by means of a compatibiliser [139].

Krause [140] states that polymer pairs can be compatible even if the polymer pair is not miscible and that the published literature does not deal consistently with the terms ’miscible’

or ‘compatible’. In the polymer industry, a compatible polymer pair is often a simple one which shows the desirable characteristics after being mixed as a solid or in solution. Often such polymer pairs are not miscible, since several amorphous phases with different compositions are present, but they are referred to as compatible for the case that there is good adhesion between the phases [140].

There are some indicators for the miscibility of polymers which are listed below, though it is no easy matter to estimate the compatibility of dissimilar polymers [138].

- Similar molecular structure
- Similar molecular weight
- Polarity

In order to investigate the miscibility of polymers, several methods exists [138–141]:

1. Study of the optical behaviour of the polymer blend to determine blurring
2. Measurement of glass transition temperatures to determine polymer phases
3. Nuclear magnetic resonance spectroscopy to investigate the polymer structure
4. Theoretical study to predict the affinity of the polymers to each other by
    a. Flurry Huggins theory
    b. Hansen parameter

In the case of joining skins and foam core, the miscibility of the polymer pair is of great interest, since the aim is to fusion bond skin and foam core with the result of obtaining high bond strength.

The following investigations are performed in the framework of this thesis in order to investigate the miscibility of skin and core polymers:

1. Fusion bonding trials followed by mechanical testing
2. Measurement of glass transition temperatures
3. Hansen parameter determination
4. Literature research for miscibility of the specific polymer pairs

4.1.3.1 Fusion bonding investigations followed by mechanical testing

The compatibility of the polymer combinations resulting from suitable available skin and core polymers is investigated by fusion bonding experiments. The different polymers, applied as films, are joined and tested according to a T-peel test (based on DIN EN ISO 11339 [142]) to investigate the bond strength.

Polymer film A and polymer film B are placed in a hot press. In order to strengthen the films for testing, the films are reinforced by a steel mesh. A polyimide (PI) film, covered with release agent (Release-All 45 by Airtech, Luxemburg) is brought between both polymer films along a specific section. The whole stack is heated in the hot press and the polymer films are, if possible, fusion bonded. The PI film functions as a crack initiator with the result that a part of the blend is not joined. The result is a sample with a bonded area and two shanks, which are needed for the T-peel test, see Figure 22.

Combining each suitable skin polymer (PEEK, PPS) with each available core material (PEI, PES, PPSU) leads to the combinations to be investigated as illustrated in Table 7.

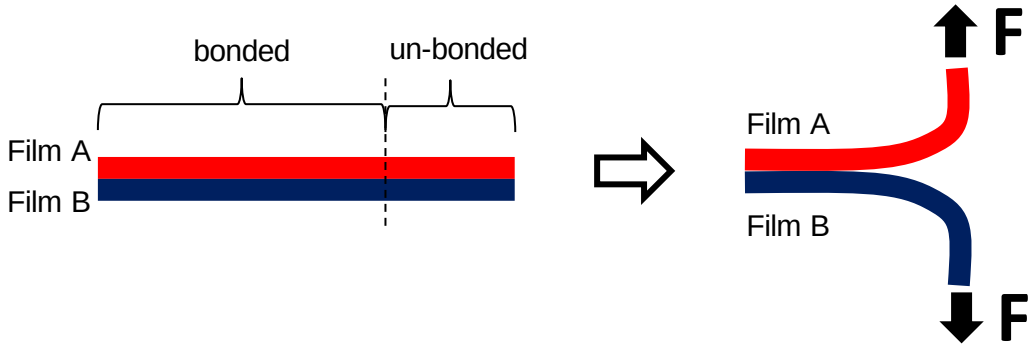


Figure 22: Film peel testing

Polymer pairs with PEEK are fusion bonded at 360 °C, 0.2 MPa pressure for 15 minutes, whereas PPS based combinations are joined at 295 °C under 0.2 MPa of pressure with a holding time of 15 minutes. 5 samples for each combination are tested.

Table 7: Polymer blend combinations for compatibility investigations (skin/core material)

		Core material				
		PEI	**PES**	**PPSU**	**PEEK**	**PPS**
Skin material	**PEEK**	PEEK/PEI	PEEK/PES	PEEK/PPSU	PEEK/PEEK	/
	PPS	PPS/PEI	PPS/PES	PPS/PPSU	/	PPS/PPS

Based on the peel test results in Figure 23 and the failure mechanisms, the miscibility of the polymer pairs can be differentiated into three categories: miscible, partially miscible (compatibility) and not miscible. The combination of PEEK/PEI leads to high peel-forces. During testing, the samples fail within a shank indicating a strong bond. The miscibility is therefore rated as good. PEEK/PEEK and PPS/PPS pairs fail as well in the shanks, indicating the right selection of processing conditions. PEEK/PPSU pairing shows partial miscibility, which might be considered according to Krause [140] as compatibility. Both films can be separated at an average peel force of 35 N.

The results of the PEEK/PES, PPS/PEI, PPS/PES and PPS/PPSU combinations show that these materials are not miscible. With low forces around 2 N the films are easily peeled off.

Microscopic pictures confirm these results. As an example, the samples of the PEEK/PEI combination show no distinct interface, leading to the assumption that molecular interdiffusion has taken place, see Figure 24a. In contrast PEEK/PPSU (Figure 24b) and PEEK/PES (Figure 24c) samples show phase separation and a clear interface, indicating that the material are not miscible but obviously in the case of PEEK/PPSU compatible as shown with the T-Peel test results.

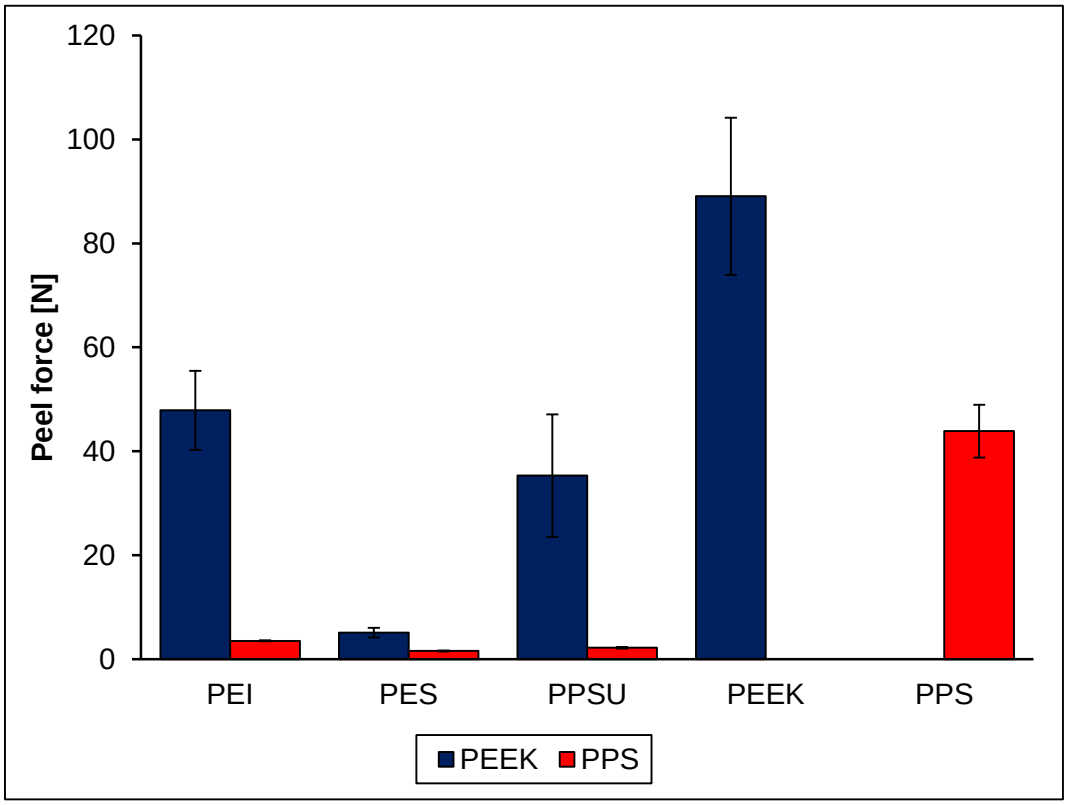


Figure 23: Compatibility of polymers: peel forces

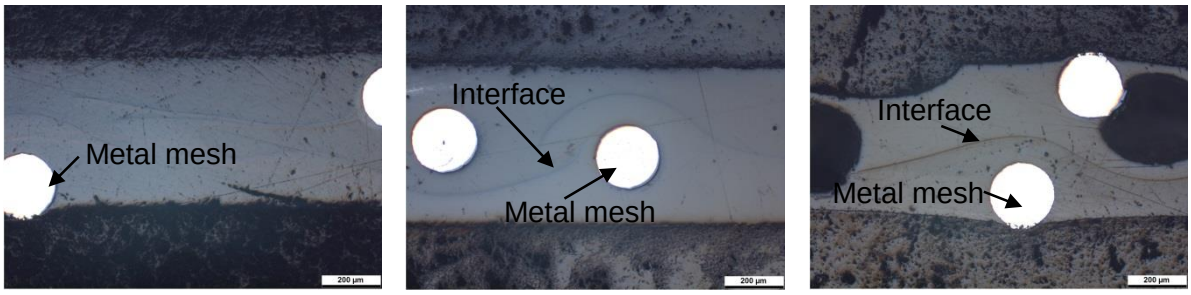


Figure 24: Interphase of a) PEEK/PEI, b) PEEK/PPSU, c) PEEK/PES

4.1.3.2 Measurement of glass transition temperatures

The most common method to determine the miscibility of a polymer pair is the measurement of glass transition temperatures (T_g) by thermoanalytical methods such as differential scanning calorimetry (DSC) [139]. The existence of a single T_g of the polymer combination indicates mixing of the polymers, whereas the appearance of two T_g*'s* indicates a two phase immiscible polymer pair [139].

Exemplarily, Figure 25 shows the DSC plot of pure PEEK and PEI as well as the DSC plot of a PEEK/PEI blend (50/50 share). The glass transition temperature of approximately 217 °C can be determined for PEI and 147 °C for PEEK. For the PEEK/PEI blend, only one T_g is

discernible at approximately 207 °C, which indicates that the polymers are miscible. The influence on the crystallisation behaviour of PEEK is discussed later in this chapter.

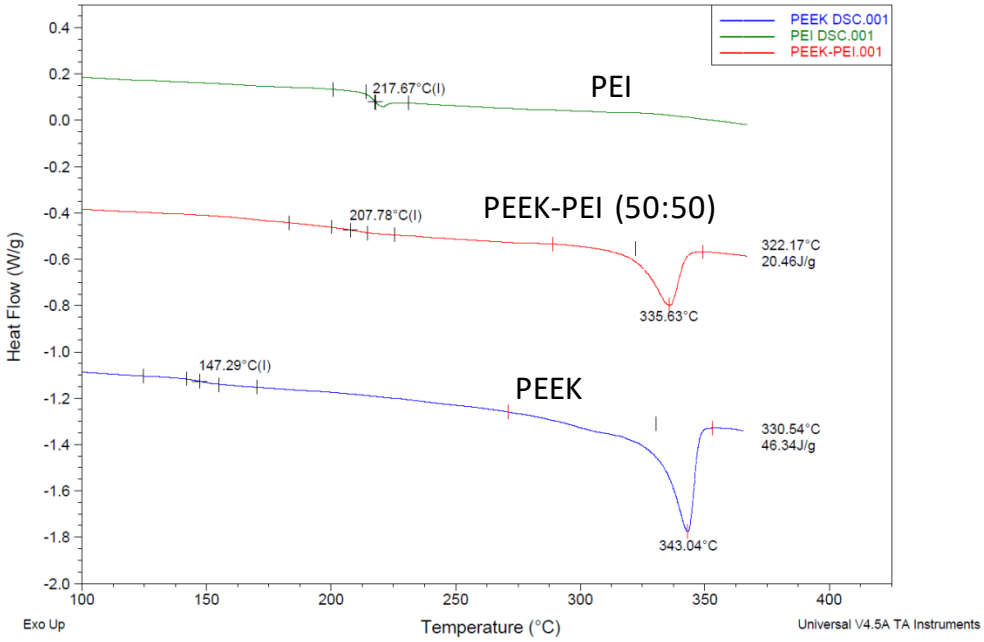


Figure 25: DSC graphs of PEEK, PEI and a PEEK-PEI blend

In comparison Figure 26 present the thermoanalysis of PEEK, PES, and the PEEK/PES (50/50 share) blend. For the virgin materials, the glass transition temperatures can be determined to be 148 °C for PEEK and 227 °C for PES. The PEEK /PES blend features two T_g's at 147 °C and 225 °C, indicating two phases.

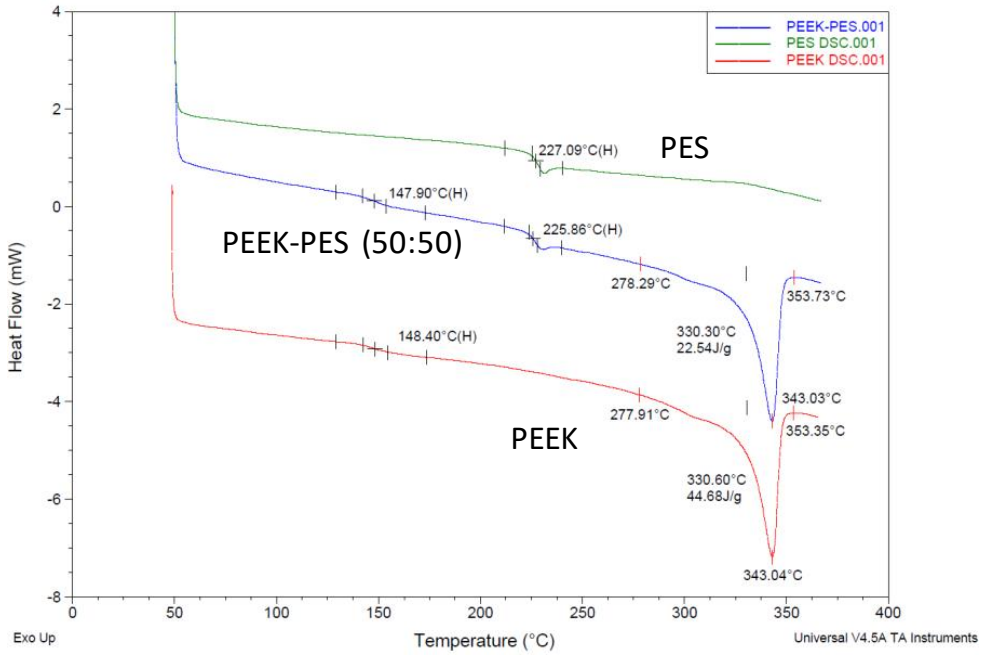


Figure 26: DSC graphs of PEEK, PES and the PEEK/PES blend

Table 8 gives a summary of the measurements of glass transition temperatures, which shows that according to this method only PEEK and PEI are miscible.

Table 8: Results from glass transition temperature measurement

		Core material		
		PEI (217 °C)	**PES (227 °C)**	**PPSU (218 °C)**
Skin material	**PEEK (147 °C)**	207 °C	147 °C/225 °C	150 °C /189 °C
	PPS (98 °C)	95 °C/211 °C	99 °C/221 °C	105 °C/210 °C

4.1.3.3 Hansen Solubility Parameter

The solubility parameter as proposed by Hansen [141,143] can be used to predict the compatibility of polymers. The theoretical basis of the Hansen solubility parameter is the interaction between polymers, which is derived from cohesive energies from interactions of a given molecule with another. There are three major types of interactions in common organic materials leading to three major cohesive energies: dispersion cohesive energy E_D, polar cohesive energy E_P and hydrogen bonding energy E_H. Dividing the energies by the molar volume leads to the three solubility parameters, namely

- δ_D = Dispersion cohesion (solubility) parameter
- δ_H = Hydrogen bonding cohesion (solubility) parameter
- δ_P = Polar cohesion (solubility) parameter

Hansen and co-workers [143] developed the ratio *RED* (Relative energy difference), which allows the prediction of polymer (between polymer 1 and polymer 2) affinity with

$$RED = \frac{Ra}{Ro} \qquad \textbf{Equation 2}$$

where *Ro* is the radius of the interaction sphere in the Hansen space and *Ra* is the distance in the Hansen space. *Ra* is defined as:

$$Ra^2 = 4(\delta_{D2} - \delta_{D1})^2 + (\delta_{P2} - \delta_{P1})^2 + (\delta_{H2} - \delta_{H1})^2 \qquad \textbf{Equation 3}$$

A *RED* number less than 1.0 indicates high affinity of the molecules, while a RED number more than 1.0 indicates progressively lower affinities. A *RED* number equal or close to 1.0 is a boundary condition [143]. Input data must be experimentally determined or derived from databases.

Table 9 gives a summary of the *RED* numbers, calculated according to the Hansen parameter for the investigated polymer combination. Data for PPSU were not available.

Table 9: Results for *RED* for several polymer blends based on data according to Hansen [143]

		Core material		
		PEI	**PES**	**PPSU**
Skin material	**PEEK**	0.2	6.6	n/a
	PPS	4.2	6.0	n/a

According to the solubility parameter of Hansen, only the PEEK/PEI pair shows affinity with each other.

4.1.3.4 Conclusion

Table 10 provides a summary of the miscibility investigations of polymer pairs suitable for skin and core materials. In addition, references found in public literature confirm the obtained miscibility results. Table 10 shows clearly, that PEEK and PEI are compatible and even miscible. Therefore, they embody a good polymer pair to be fusion bonded for sandwich manufacturing.

Table 10: Summary of investigations concerning miscibility of polymer blends

Polymer pair	Fusion bond & peel testing	T_g measurement	Hansen	Literature	
PEEK/PEI	+	+	+	+	[144]
PEEK/PES	-	-	-	-	[145]
PEEK/PPSU	0	-	n/a	-	[146]
PPS/PEI	-	-	-	-	[147]
PPS/PES	-	-	-	0	[148]
PPS/PPSU	-	-	n/a	0	[149]

where + indicates miscibility, 0 partial miscibility /compatibility and – incompatibility/immiscibility

Therefore, the materials that will be considered in this study are:

- Skin: CF/PEEK
- Core: PEI foam core

In the following sections these materials will be discussed in more detail.

4.2 MATERIALS – PROPERTIES

4.2.1 Polyetheretherketone

Polyetheretherketone (PEEK) is a semi-crystalline high-performance polymer, which belongs to the polyaryletherketone (PAEK) family [107,150]. The polymerisation of PEEK was first conducted in 1962 [151]. PEEK was originally developed for the aerospace industry, but due to its excellent mechanical properties, high temperature and chemical resistance it is today appreciated in several other industries such as dental medicine [152]. The structural formula of PEEK is illustrated in Figure 27.

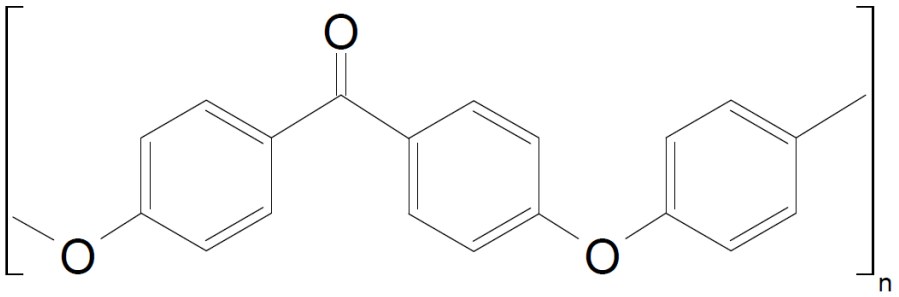


Figure 27: Structural formula of PEEK

Some properties of PEEK are summarised in Table 11.

Table 11: Properties of Polyetheretherketone [107,151]

General properties	Unit	Value	Test standard
Density	g/cm³	1.32	ISO 1183-1
Moisture take-up	%	0.2	ISO 62
FST	-	V0/V0	UL 94
Mechanical properties			
Yield Stress	MPa	97	ISO 527
Ultimate elongation	%	> 60	ISO 527
E-Modulus (Tensile)	MPa	3600	ISO 527
Thermal properties			
Melting temperature	°C	~343	ISO 11357
Glass transition temperature	°C	~143	ISO 11357
Service temperature (long time)	°C	-65 - +240	-
Thermal conductivity	°C	0.25	DIN 52 612

4.2.2 PEEK used in skin material

In this study carbon fibre reinforced PEEK is applied as skin material. Primarily skins reinforced with carbon fibre fabrics but also unidirectional (UD) tapes are used. The composite materials are summarised in Table 12.

Table 12: Properties of the CF/PEEK composite materials [153–155]

Reinforcement	Fibre	Fibre areal weight	FVC	Supplier
Fabric 5HS	3K HS	285 g/m²	58 %	Toho Tenax
Fabric 4HS	3K HS	220 g/m²	56 %	Porcher Industures
UD Tape	12K HTS45	145 g/m²	66 %	Toho Tenax

4.2.3 Polyetherimide

Polyetherimide (PEI) is an amorphous high-performance polymer, which was developed in the early 1980s [156]. The structural formula is presented in Figure 28. PEI is appreciated for its good mechanical properties and high temperature resistance. However, due to the amorphous character, PEI has some drawbacks concerning chemical resistance to Dichlormethane (DCM) or Skydrol®, for example [107].Table 14 presents several properties of PEI.

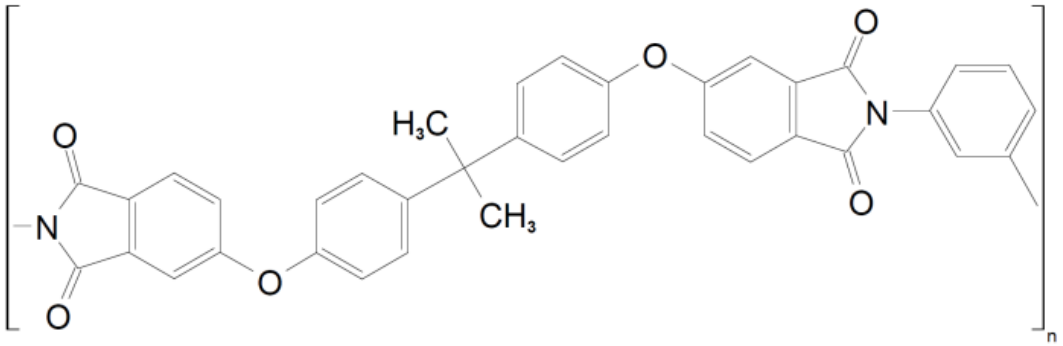


Figure 28: Structural formula of PEI

4.2.4 PEI used as core material

In this study, PEI is used as the core material in form of a closed cell foam. The PEI foams Airex® R.82 provided by Gaugler and Lutz, Germany with two different densities, namely 60 kg/m³ and 110 kg/m³, are used. The foam properties are summarised in Table 13.

Table 13: Properties of Airex® R.82 foams [96]

Property	Test standard	Unit	R.82.60	R.82.110
Density	ISO 845	kg/m³	60	110
Compression strength	ISO 844	MPa	0.7	1.4
Tensile strength	ISO 527 1-2	MPa	1.7	2.2
Shear strength	ISO 1922	MPa	0.8	1.4
Thermal conductivity	ISO 8301	W/mK	0.036	0.04

Table 14: Properties of Polyetherimide [107,157]

General properties	Unit	Value	Test standard
Density	g/cm³	1.27	ISO 1183-1
Moisture take-up	%	0.5	ISO 62
FST	-	V0/V0	UL 94
Mechanical properties			
Yield Stress	MPa	105	ISO 527
Ultimate elongation	%	60	ISO 527
E-Modulus (Tensile)	MPa	3200	ISO 527
Thermal properties			
Melting temperature	°C	-	ISO 11357
Glass transition temperature	°C	~217	ISO 11357
Service temperature (long time)	°C	-100 – +170	-
Thermal conductivity	°C	0.24	DIN 52612

4.2.5 PEEK-PEI blend

Investigations showed that blends of PEEK and PEI are found to be molecularly miscible in all compositions [144]. Furthermore, several studies revealed that blending of PEEK and PEI leads to a change of various properties such as glass transition temperature, solvent resistance, crystallisation rate and toughness. Crevecoeur et al. [158] studied the crystallisation behaviour of PEEK in its blends with PEI using thermal analysis and small angle x-ray scattering. He showed that PEI only weakly influences the crystallisation of PEEK and the melting temperature of PEEK is only slightly depressed by the addition of PEI. Moreover, by blending PEEK and PEI the amorphous phase is enriched in PEI, so the glass transition temperature increases. Harris et al. [159] studied the mechanical behaviour of PEEK/PEI blend in different compositions. Their results show that by blending PEEK with PEI, the tensile strength and the tensile impact strength are increased in comparison to pure PEEK, while the tensile modulus and the notched izod strength are slightly decreased. Furthermore, it was revealed that additional annealing influences the properties significantly. Thereby, the composition influences the change of the properties. In addition, Harris et al. [159] investigated the influence of blending PEEK and PEI on chemical resistance in comparison to pure PEEK. He found that adding PEI leads to a decrease of the mechanical properties (stress crack resistance) after treatment with chemical substances such as toluene or trichloroethylene. However, at a small fraction (< 30 %) of PEI, the mechanical behaviour is only slightly influenced as illustrated in Figure 29.

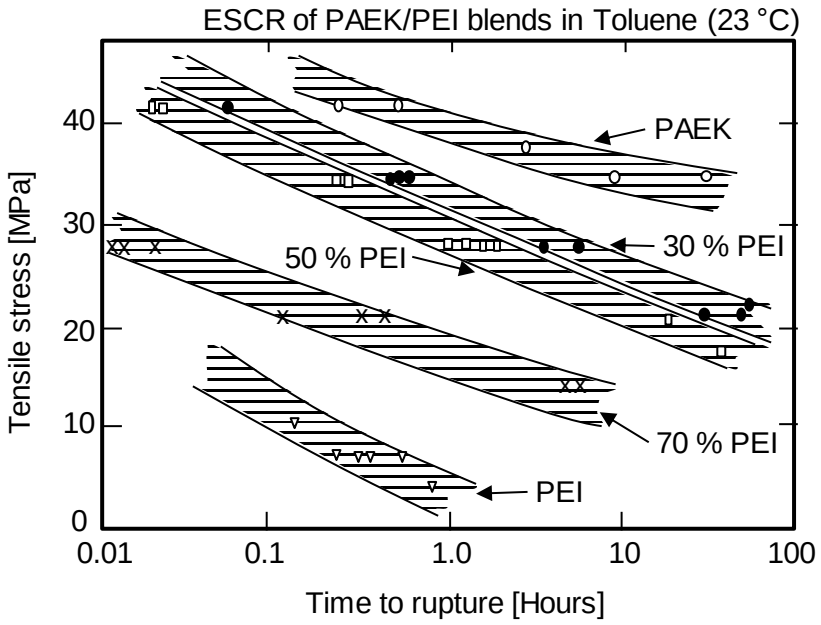


Figure 29: Influence of blending PEEK and PEI on the chemical resistance according to Harris et al. [159]

Based on results presented above, and due to the fact that blending during fusion bonding of CF/PEEK skins and a PEI foam core will only occur at the inner surface of the skins or to the surface of the core, it is assumed that blending will not significantly influence the properties of the skins and core.

4.3 MANUFACTURING PROCESS SELECTION

As presented in chapter 2.2, there are different manufacturing methods for the production of thermoplastic composite sandwiches which can be categorised into adhesive and cohesive joining. Adhesive joining is a simple technique that does not influence the properties of the individual sandwich constituents. However, intensive surface preparation and a poor bond strength might result from this technique [22,100]. Adhesive joining is therefore not further pursued in this study.

Fusion bonding is based on the interdiffusion of molecules across the surface leading to a cohesively strong joint between the adherents and can additionally be realised in short cycle times [109,111]. Several manufacturing techniques based on fusion bonding have been presented in public literature. In the following section these techniques are evaluated for the ability of manufacturing 2D and 3D sandwich structure for helicopter applications according to criteria worked out in accordance with the advantages and disadvantages of the manufacturing methods and by using the requirements presented in chapter 1.2.

4.3.1 Evaluation and selection

Table 15 shows the evaluation of the manufacturing processes according to several criteria. Where a manufacturing process is evaluated with "- -" for any criterion, the process will not be further pursued (knock out - criterion).

Table 15: Manufacturing process evaluation

Manufacturing methods	Sandwich properties		Cost		Application			Processing			
	Prevention of core crushing	Expected skin quality	Equipment costs	Infrastructure available for the study?	Applicable for high performance polymers	3D possible?	Various configurations possible?	Ease of operation	Cycle time	HSE requirements	Total
Vacuum moulding – isotherm	- -	0	+	+	+	+	+	+	0	+	**- -**
Vacuum moulding - non-isotherm	0	-	+	+	- -	+	+	0	+	+	**- -**
Compression moulding – isotherm	- -	0	0	+	+	+	+	+	0	+	**- -**
Compression moulding - non-isotherm	0	-	0	+	+	+	+	0	+	+	**5+**
Double belt moulding	+	+	-	- -	0	-	+	+	+	+	**- -**
Film foaming	+	+	+	+	+	-	- -	+	+	-	**- -**
Injection foaming	+	+	-	- -	-	+	+	0	+	0	**- -**
Bead foams	+	+	-	- -	-	+	+	+	+	+	**- -**
Solvent bonding	+	+	+	+	0	+	+	+	+	- -	**- -**

With **+** = positive, **0** = neutral/ evaluation not possible, **-** = negative and **- -** = k.o.

The evaluation shows that only the non-isothermal compression moulding process seems to be suitable and feasible for manufacturing of TPC within the framework of this study.

Isothermal processes cannot be applied to manufacturing since the whole sandwich setup, consisting of skins and core is heated and compressed, leading to core collapse. These methods are only feasible in specific cases where the foam features a higher softening temperature than the skins. Double-belt moulding cannot be investigated in this project, since the infrastructure is not available and only 2D sandwich plates can be produced. In contrast, film foaming is a promising technique to produce sandwiches based on high performance polymers such as PEI. Sandwiches manufactured with this method are already commercially available, though the method is only applicable for sandwiches with thin skins (limited number of plies) and for some matrix polymers, because the blowing agent has to evaporate during processing and requires permeable skins. Meanwhile, in-situ foaming techniques such as injection moulding or particle foams show great potential for the production of TPC sandwiches. However, the infrastructure of such machines and tools is not available within the framework of this study and therefore cannot be further pursued. Moreover, further research in foaming of high performance polymers has to be performed to make this technique suitable for aviation applications. Solvent bonding is a promising technique which can be conducted in short cycle times. Skins and core are not influenced, since the solvent is applied only superficially on skins and foam. However, the chemical substances usually required for dissolution of the polymer can be hazardous to health and have a negative impact on the environment for dissolution of the polymers, and therefore the method shall not be investigated in this study.

4.3.2 Non-isothermal compression moulding process

The basic idea of non-isothermal compression moulding is that the sandwich is produced in a two-step pressing process. First the skins are heated separately, before being stacked on the core and consolidated under pressure. During the process, heat energy is transferred from the skins into the core, with the aim of softening the core only superficially while the main structure of the core stays relatively cold. This allows fusion bonding of skins and core, while the core centre remains stable and core collapse can be avoided.

Summarising, the advantages (+) and disadvantages (-) of the non-isothermal compression moulding process are:

+ Non-isothermal heating reduces the risk of core collapse, since the core centre is not heated above the softening temperature.
+ Machines and equipment are available. Therefore, this method seems to be realisable within the frame work of this study.
+ Compression moulding is state-of-the-art technology for processing of high performance polymers. Therefore, the machinery is dimensioned for the high temperatures involved.
+ Since only the skins (low mass) are heated, the non-isothermal process is appreciated for its short cycle times.
+ The process is flexible for part dimensions (2D, 3D) as well skin and core thicknesses.
- Possible de-consolidation of the skins during the heating process, since no pressure is applied on the laminates. This might further narrow the process window.

5. PROCESS DEVELOPMENT

5.1 PRE-TRIALS

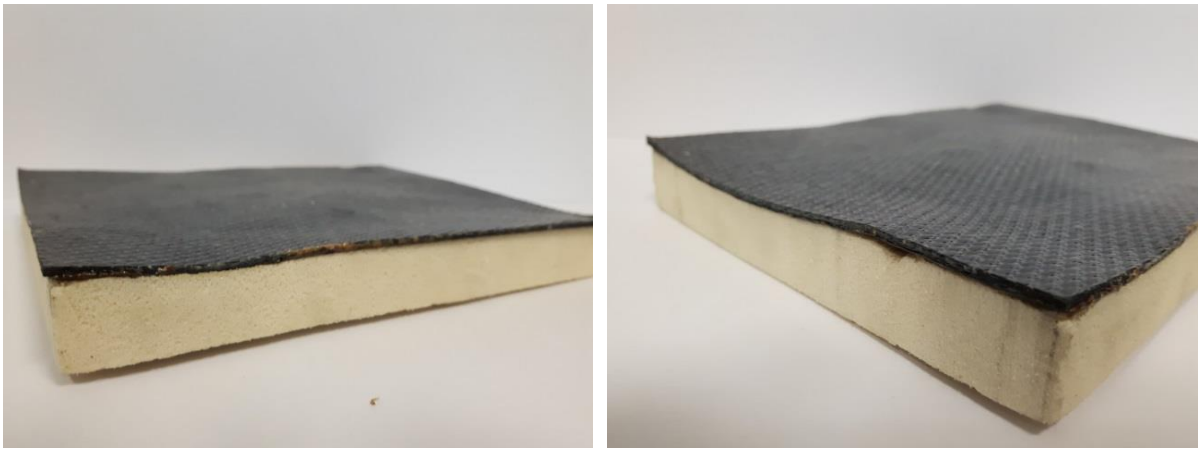
As discussed in chapter 2.2, a good bond between skins and core needs to be achieved to obtain a thermoplastic composite (TPC) sandwich of sufficient quality, which this study aims to realise by means of fusion bonding. For this, fusion bonding requires the skins as well as the core, more precisely the core surface, to be molten in order to allow molecule interdiffusion [113].

The following chapter describes fusion bonding investigations of carbon fibre reinforced Polyetheretherketone (CF/PEEK) skins and a Polyetherimide (PEI) foam core by means of non-isothermal compression moulding. Materials and process have been selected according to aviation requirements, see material and process selection in chapter 4. To enable molecular mobility for the fusion bonding process, the PEEK based skin material must be heated above its melting temperature (T_m) of ~343 °C, see chapter 4.2.1. Meanwhile, the PEI based foam core needs to be processed at temperatures above ~217 °C (glass transition temperature (T_g) of PEI), see chapter 4.2.3.

In first experimental trials, the skins (consolidated CF/PEEK laminates, 8 plies of 5HS fabric 285 g/m², see chapter 4.2.2) are heated in a circulating air oven (NA 500/45, Nabertherm, Germany) above a temperature ($T_{Skin\ pre\text{-}heat}$) of 350 °C ($T_{Skin\ pre\text{-}heat} > T_m$(PEEK)), transferred into a press (Platenpress P 400 P, Dr. Collin GmbH, Germany) and placed on top of the cold (core temperature T_{Core} = 23 °C) PEI foam core before being consolidated under a pressure of 0.2 MPa. To simplify the process, the skins were joined separately to each core side. However, the pre-trials revealed that this method of joining of CF/PEEK skins to a PEI foam core is not readily possible due to several challenges.

The skin laminates soften during heating in the oven. Transferring the skins from the oven to the press leads to deformation of the skin shape during their handling. Even though the skins are placed on top of the core and loaded by the press, the initial shape cannot be restored. Indeed, deformation of TPC blanks during transfer is a common phenomenon of thermoplastic composite processing such as hot stamping. It is referred to as sagging and is often caused by gravity during heating and transfer [160]. However, during stamp forming the initial shape can be restored (or the desired shape be realised) since the composite blank is pressed into a steel mould. Unfortunately in the sandwich case, the desired composite skin shape cannot be restored since the core cannot withstand the temperature and pressure and is compacted unevenly or collapses, as illustrated in Figure 30.

Moreover, it is observed that the initial fully consolidated skin laminates show a porous and open structure after the joining process, see Figure 31. In public literature the phenomenon of ‘lofted’ skin layers after heating has been reported by several researchers of thermoplastic composite processing [161–165]. The change of the laminate structure is referred to as thermal de-consolidation [161]. Experiments [164,165] revealed that the initially well consolidated laminates have a significant negative change in their meso-structure as well as in their macro-performance when exposed to heat.



a) b)

Figure 30: a) Deformed skin laminate and b) unevenly compacted core at a skin processing temperature above 350 °C

Rozant et al. [71] also report on the de-consolidation phenomenon during TPC sandwich processing and considers de-consolidation as one of the limiting phenomena of TPC processing. Akermo et al. [39] describe fibre lofting during sandwich processing and highlights that the skins cannot be compressed to the initial thickness on the foam core. De-consolidation is explained by different mechanisms such as release of the elastic energy stored in the fibre reinforcement after compaction [71,163] or the release of thermal stress induced by non-uniform temperature fields [164]. Thermal de-consolidation is associated with an increase in void content, which can increase by 10 % - 20 % [161]. According to [165] the flexural strength of glass fibre reinforced Polyamide12 composite sheets decreases by about 38 %, when the void content increases from 1 % to 12 %. Therefore, thermal de-consolidation must be avoided in order to prevent weakening of the skins and of the sandwich as a whole.

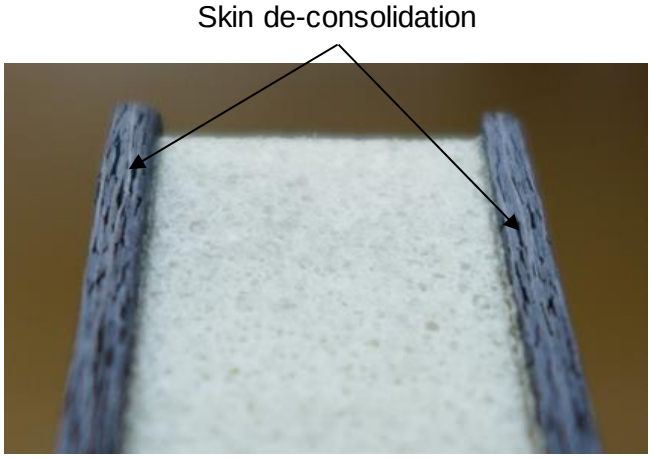


Figure 31: Porous skin laminates

Figure 32 shows the de-consolidation behaviour of CF/PEEK laminates (3 plies) when heated to different temperatures (330 °C – 390 °C) in the absence of pressure in comparison to an initial fully consolidated laminate.

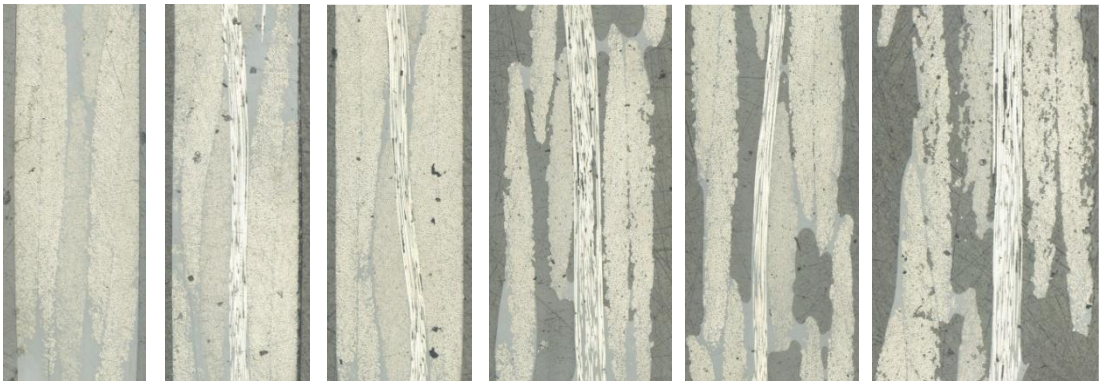


Figure 32: De-consolidation of CF/PEEK laminates at different heating temperatures in the absence of pressure in comparison to an initial fully consolidated laminate

Several trials attempting to re-consolidate the laminate on the foam did not succeed. The laminates still possessed a high void content. Processing conditions for re-consolidation of CF/PEEK laminates will be discussed in more detail in chapter 9. In addition, during processing the core was compacted to a high extent, see exemplarily Figure 33. Core compaction is thereby defined as (sort of controlled) compression of the core under heat and pressure, whereas core collapse takes place in an uncontrolled manner caused by extensive heating.

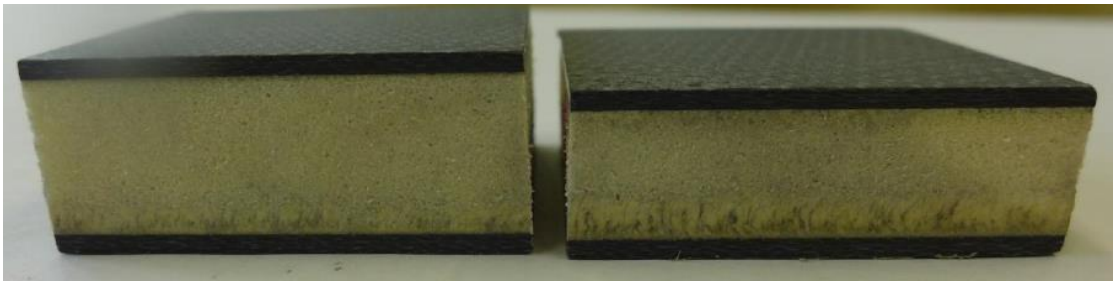


Figure 33: Core compaction caused by extensive heating of the skins

In contrast, by reducing the skin pre-heat temperature to below 343 °C (T_m of PEEK) to avoid de-consolidation, loss of form-stability of the skins as well as core compaction and collapse, a bond between skin and core cannot be realised (see Figure 34). Joining by fusion bond is restricted by the lack of mobility of the PEEK material, while adhesive joining by flowing of the molten PEI polymer (the surface of the PEI core is obviously softened without collapse of the core) into the surface of the PEEK laminate and creating inter-mechanical locking is hindered by the low surface energy of PEEK leading to low wetting [166].

Summarising, to prevent skin sagging and de-consolidation the skin temperature should be below the melting temperature of PEEK ($T_{Skin\ pre\text{-}heat} < T_m$(PEEK) = ~343 °C). To avoid core collapse, pressure and temperature should be kept at a minimum. However, although skin temperatures below T_m of PEEK lead to superficial softening of the core without collapsing, a bond between skins and core cannot be achieved. Therefore, another solution is required to establish fusion bonding of skins and core.

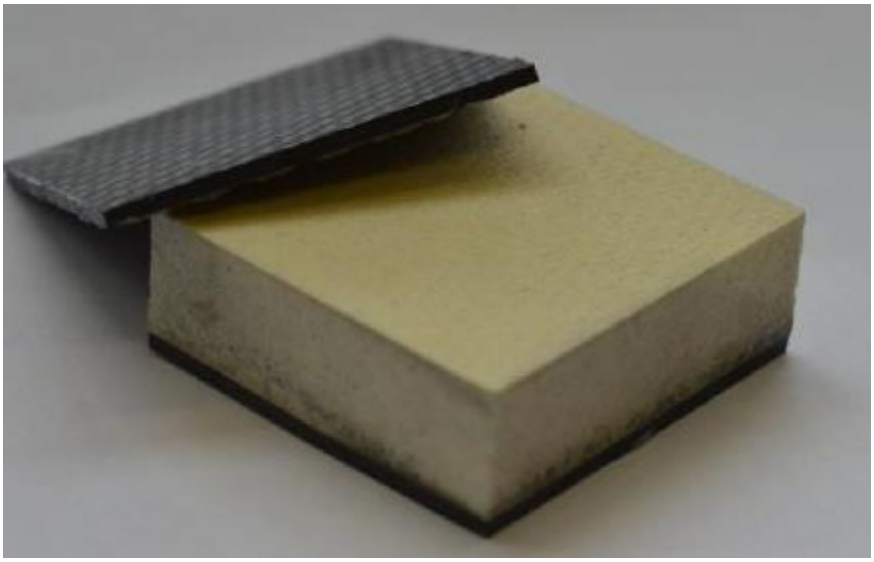


Figure 34: Joining of skins and core at skin pre-heat temperatures below 343 °C could not be realised

5.2 PROCESS ADAPTATION

To enable a fusion bond between CF/PEEK skins and a PEI foam core by means of compression moulding, the process is adapted to the concept of the 'Thermabond' process [167]. The basic idea of the 'Thermabond' process is that thermoplastic (preferably semi-crystalline polymer based) composite parts are bonded with the aid of a second polymer system (preferably amorphous based) with a lower softening temperature than the first polymer. However, this second polymer is not applied as a hot melt film, but rather a cohesive bond between the two polymers is created [167]. Therefore, the thermoplastic composites to be joined are superficially enriched with the second polymer system by fusion bonding. In the case of manufacturing TPC sandwiches according to the 'Thermabond' principle, the CF/PEEK skins are superficially enriched on one side with a PEI film at temperatures above the T_m of PEEK, as illustrated schematically in Figure 35.

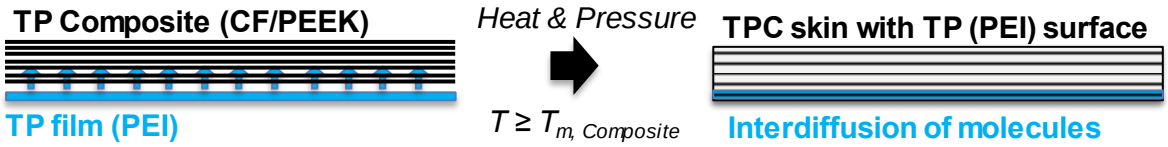


Figure 35: 1st step of the manufacturing process of TPC sandwich adapted to the 'Thermabond' principle

In a following step the two parts to be joined, in this case skins and core, are fusion bonded by means of heat and pressure. According to the non-isothermal compression moulding process, heat is introduced mainly by heating the skins, whereas the core can be pre-heated or kept at room temperature. However, it is aimed to keep the core, more precisely the core centre below the softening temperature ($T_{Core\ centre} < T_{g,Core}$) to maintain its form-stability. By heating the skins, the surface-enrichment-layer (PEI layer) is heated sufficiently above the softening temperature ($T_{Skin} > T_{g,TP\ enrichment} = T_{g,(PEI)}$) to enable molecular diffusion, yet not so high as to melt the composite polymer of the skin ($T_{Skin} < T_{m,\ Composite} = T_{m(PEEK)}$). This allows the physical and

mechanical properties of the CF/PEEK skins to be not compromised. The molecular mobility of the PEI foam surface is enabled by heat transfer from the skins into the core surface, while the core centre stays relatively cold. The joining step is illustrated in Figure 36.

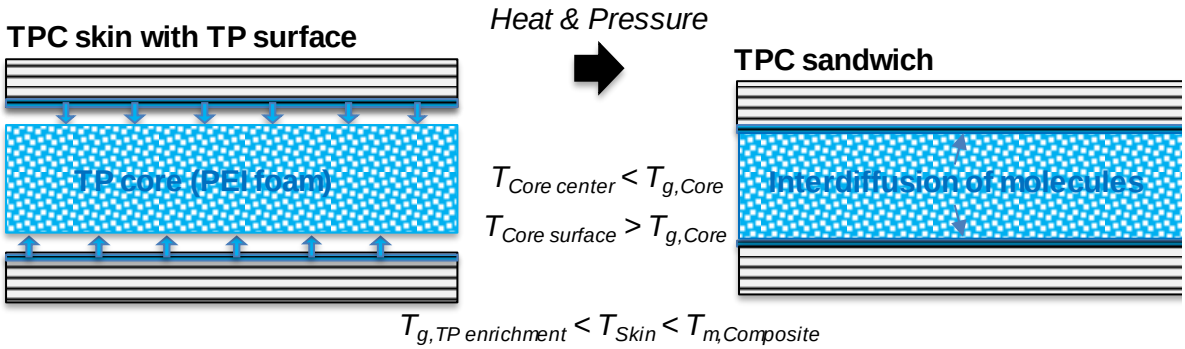


Figure 36: 2nd step of the manufacturing process of TPC sandwich adapted to the 'Thermabond' principle

By adapting the 'Thermabond' process, CF/PEEK skins and the PEI core can be theoretically joined in the temperature range T_g(PEI) < ~220 °C – ~340 °C < T_m(PEEK), however more likely is the range of 260 °C – 320 °C according to [167], as illustrated in Figure 37. The viscosity of PEI is low enough for molecular diffusion. PEEK still shows a high form-stability over the temperature range and the properties are not compromised.

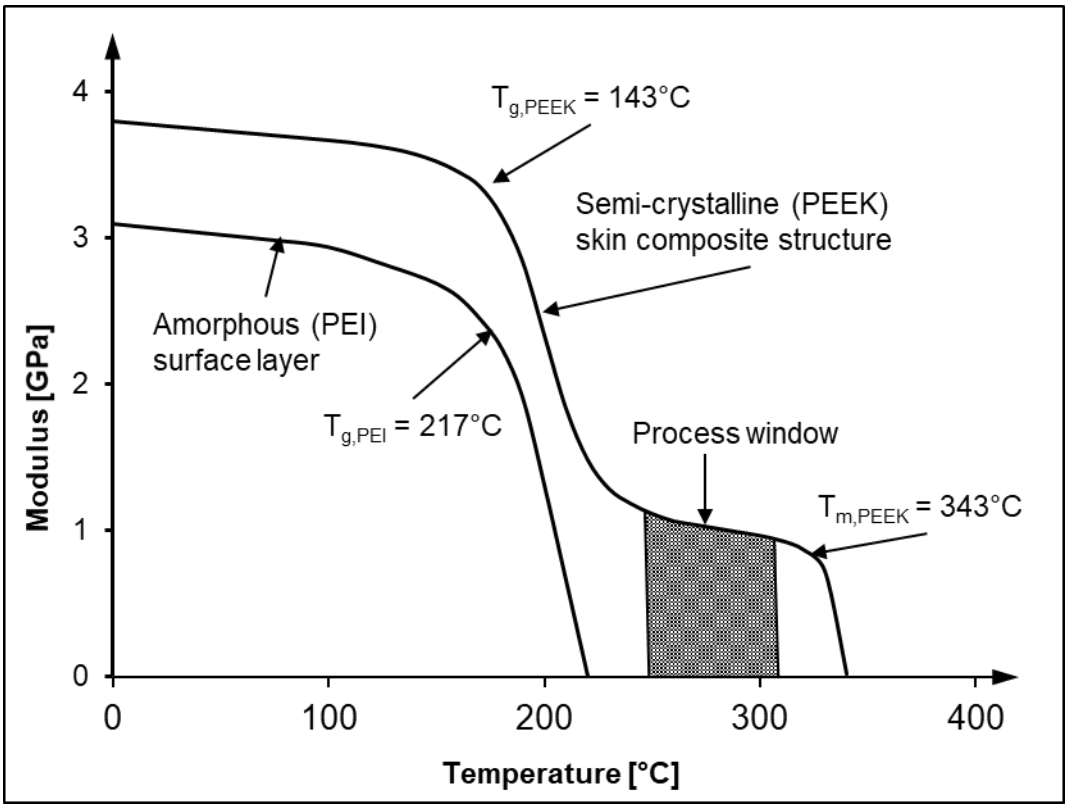


Figure 37: Process window for fusion bonding CF/PEEK skins and PEI core enabled by the 'Thermabond' principle according to Smiley et al. [167]

Adapting the non-isothermal compression moulding process to the ‘Thermabond’ process offers several advantages:

- Enriching the CF/PEEK composite skins with the PEI film by means of fusion bonding in a separate step, high temperatures and pressure are only acting on the composite skin which can withstand these processing conditions. Furthermore, composite sagging and de-consolidation do not pose a challenge since the joining step can be conducted in steel tools which allow consolidation or re-consolidation, by means of high pressure. Skins of high quality featuring, for example, low void content can be realised.
- By keeping the skins below the melting temperature of the skin composite matrix material during the skin-to-core joining, the skins are form-stable and mechanical properties are not compromised. Sagging and de-consolidation do not challenge the process.
- Processing the skins at lower temperatures, the risk of core collapse and compaction due to extensive heating is reduced since less energy is transferred to the core.
- CF/PEEK skins and the PEI film enrichment as well as skins and the PEI foam core are joined by fusion bonding, which results in a high bond strength.

5.3 SKIN PREPARATION

The superficial PEI enrichment of CF/PEEK is first performed by vacuum moulding. This technique uses atmospheric pressure and temperature to fusion bond PEEK and PEI. An advantage of the vacuum bagging technique is that this technique ensures an evenly distributed pressure on the parts to be joined. The initial, fully consolidated CF/PEEK laminates (8 plies of 5HS fabric with a fibre areal weight of 285 g/m² per ply) are stacked with a PEI film (on one side) and sandwiched between two release films. A caul plate on top supports the pressure transfer on the CF/PEEK/PEI stack. An additional breather ensures air-circulation. The setup is covered with a vacuum bag, which is sealed by means of sealant tape. A valve in the vacuum setup allows the evacuation of air out of the bag. The setup is heated to 380 °C and held at this level for 20 minutes before cooling down. Figure 38 shows a microscopic picture of cross section of a CF/PEEK laminate with a PEI layer at the surface, in which it is clearly visible (in Figure 38 highlighted with red circles) that a small amount of PEI (PEI nests) has flowed into the PEEK structure. Further investigations reveal that a minimum PEI film thickness of 150 µm is required to ensure a fully covered surface.

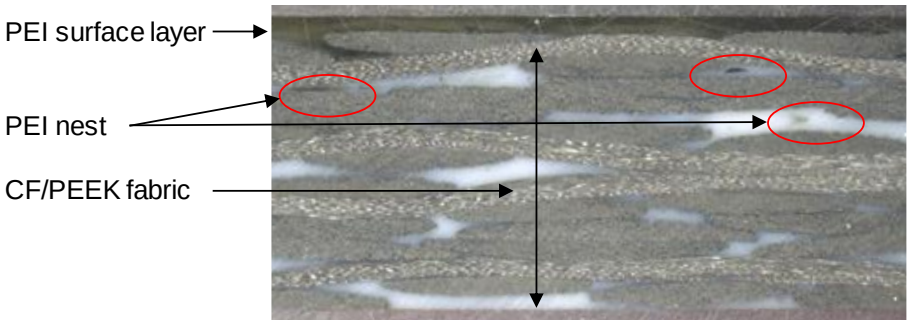


Figure 38: CF/PEEK laminate enriched with PEI on the surface by vacuum moulding

The production of the skins by means of vacuum moulding is time intensive and requires several manual labour steps, which contradicts the aim of this study to realise short manufacturing cycle times. However, this step can be done by commercial companies with

equipment that enables faster processing. Besides, as the skin-to-core bonding process is the main topic of investigation, it was decided to keep persist with this process for the first trials (trials in chapter 5) in this thesis. Consolidated skins, consisting of 8 plies $(0°,90°)_8$ of the 5HS fabric reinforced PEEK (chapter 4.2.2) are used and enriched with 150 µm PEI film.

In investigations performed at a later time (trials in chapter 6 and following), compression moulding is used to consolidate the CF/PEEK laminates while simultaneously enriching the surface with PEI. This enables the direct production of CF/PEEK-PEI skins without the need for a separate labour-intensive step. The PEI is stacked with the CF/PEEK prepregs and consolidated at 375 °C with 1 MPa pressure for 5 minutes. However, first trials showed that the PEI diffuses to a greater extent into the CF/PEEK structures and through the structure for skins with only three plies. By applying CF/PEEK unidirectional (UD) layers between the PEI film and the CF/PEEK fabric, the flow of PEI into the laminates can be reduced, since the UD reinforcement hinders the PEI in diffusing through the fibre layer. Due to the fact that this study is concerned with the application of fabric reinforced skins, to enable a comparison to thermoset reference sandwiches at a later time (chapter 7), a good compromise involves replacing only the upper (adjacent to the PEI layer) fabric ply, by two UD layers. Figure 39 shows the profile of the laminate consisting of seven fabric plies $(0°,90°)_7$, two UD layers (0°,90°) and a 125 µm PEI layer at the upper skin surface.

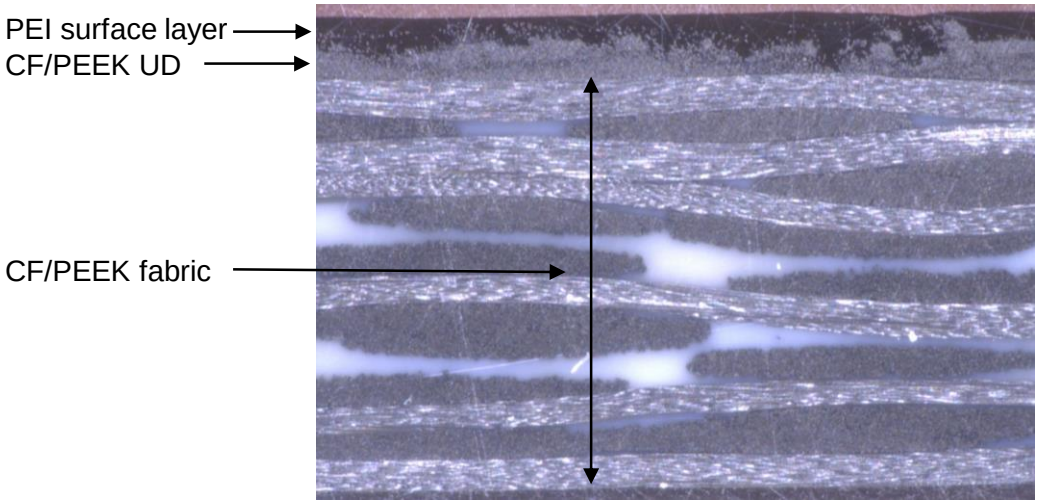


Figure 39: CF/PEEK laminate consisting of seven fabric plies, two UD plies and the PEI surface layer

Further investigations show that the use of the UD layers has the advantage of less PEI being required to enrich the surface, since the amount of PEI which diffuses into the CF/PEEK structure is reduced. Moreover, interlaminar shear strength (ILSS) reveals that if PEI flows into the structure (CF/PEEK+PEI), the composite laminate is weakened after chemical contact such as with Dichloremethane (DCM) in comparison to pure CF/PEEK laminates, see Figure 40a. In the case of unalloyed superficial PEI enrichment resulting from the application of UD layers (CF/PEEK-UD+PEI) the quality is not influenced by chemicals compared to pure CF/PEEK laminates with UD layers (CF/PEEK-UD), see Figure 40b.

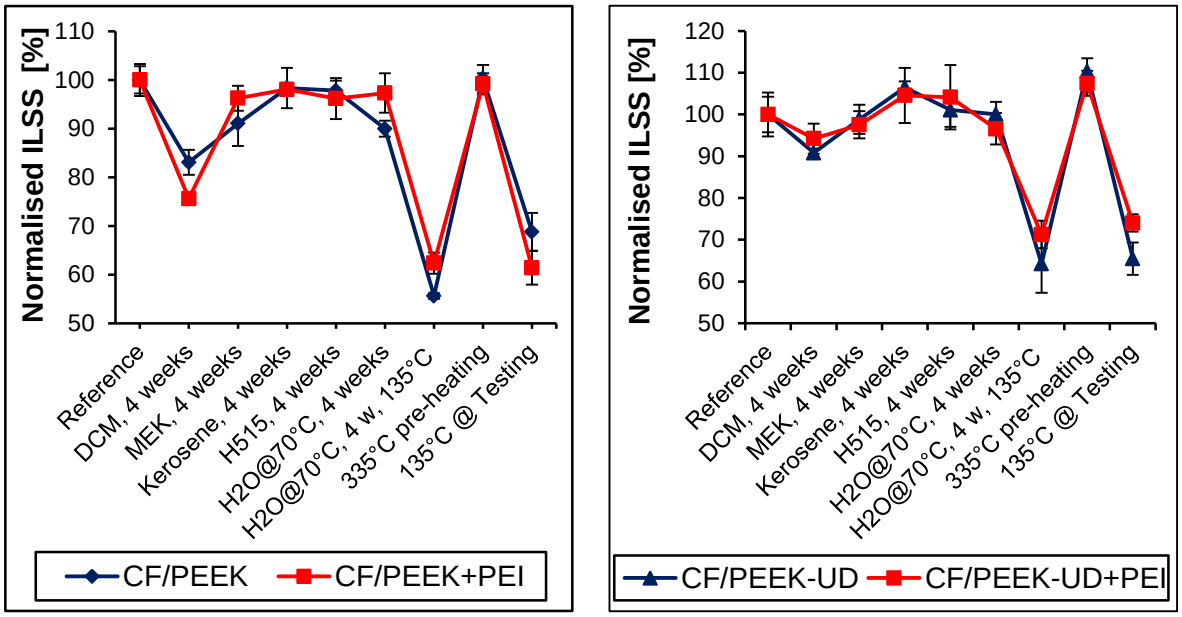


Figure 40: Normalised (to reference without treatment) ILSS testing results of a) CF/PEEK and CF/PEEK + PEI laminates after conditioning and b) CF/PEEK-UD and CF/PEEK-UD + PEI laminates after conditioning

5.4 DEFINITION OF PROCESS PARAMETERS

To understand the adapted non-isothermal compression moulding process for CF/PEEK skins and a PEI foam core, and to determine a suitable processing window, the influence of processing conditions shall be studied. Since the process is complex, the investigations will only focus on the influence of the following processing parameters, see Figure 41.

According to healing theory (chapter 2.2.2), both interface temperature and process time play a major role during fusion bonding, since molecular mobility needs to be provided. The temperature during non-isothermal compression moulding can be influenced by the **skin temperature** ***(T_{Skin})*** and the **core temperature** ***(T_{Core})***. Since the compression moulding process is implemented non-isothermally in this study, **processing time (*t*)** cannot be directly influenced, but rather depends on the skin and core temperatures. Furthermore, **pressure *(p)*** is needed to ensure intimate contact and thereby to allow interdiffusion of the molecules, though it does not influence the interdiffusion process of the molecules [168]. Due to the pressure sensitivity of the core, the aim is to keep the pressure as low as possible. Therefore, intimate contact will be established by the **core compaction distance** ***($d_{compaction}$)*** of the skins into the core at the lowest possible pressure. The core compaction distance is the difference between the initial core height and the aimed core height after controlled compaction. A variation of the initial core height leads to a variation of the core compaction distance. The core compaction distance is distance-controlled, realised by the mould stops which allows controlled core contact, more precisely core compaction, but hinders extensive compaction of the core. It is assumed that the core will be compacted only in the outer core area, more specific in the area which is softened, leading to a density gradient within the core structure.

In addition, it is assumed that the **PEI film thickness *(h_{PEI})*** can have an influence on the bond quality, since PEI is needed on both surfaces to ensure wetting and molecular interdiffusion.

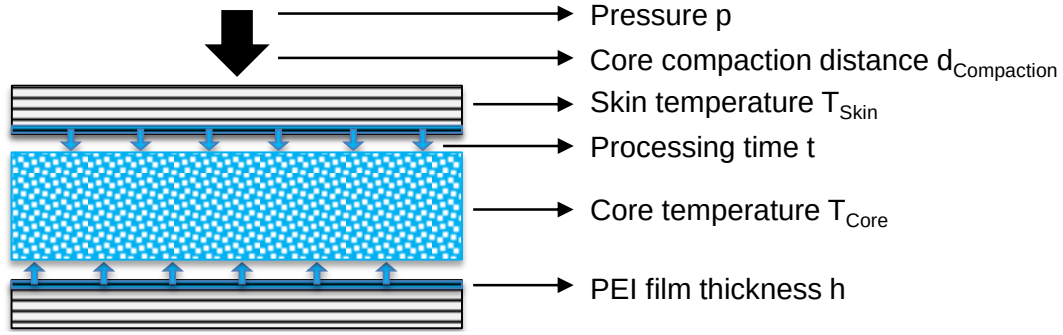


Figure 41: Process influencing parameters

The following section focuses on the influence of the process parameters ***T_{Skin}*** and ***T_{Core}***. The influence of other parameters is presented in chapter 6.

5.5 DETERMINATION OF PROCESS WINDOW – THEORETICAL APPROACH

In this section, the fusion bond process is approached theoretically, in order to identify the governing process mechanisms and to simplify the determination of the process window by experimental trials. Firstly, a theoretical background for fusion bonding is given, which provides an understanding of the governing process parameters affecting the quality of the skin-to-core bond. Secondly, a theoretical approach is deduced for the compression moulding process of sandwiches. Thirdly, tensile bond strengths in flatwise plane between skins and core are predicted depending on varying skin and core temperatures. By comparing the calculated tensile bond strengths to the tensile properties of the core, expected failure mechanisms are prognosticated. Finally, the theoretical approach is verified by experimental trials.

5.5.1 Theoretical background

Fusion bonding of thermoplastic materials aims to join two parts in order to produce one structure, with the strength of its joint approaching that of the parent materials [169]. Since the quality of the final part depends on the quality of the joint, it is important to understand the parameters affecting joint strength, including material properties and process conditions [170]. Fusion bonding involves the application of heat and pressure to the interface between the two parts to be joined. This usually requires temperatures above the glass transition temperatures (T_g) for amorphous polymers and above the melting temperature (T_m) for semi-crystalline polymers in order to lower the viscosity and to allow a high mobility of the polymer molecules [171]. The parts to be joined are then brought in contact under pressure. In theory the development of a fusion bond is divided into five steps [169,172]: 1) surface arrangement, 2) surface approach, 3) wetting, 4) diffusion and 5) randomization. These steps can be combined and two main mechanisms that contribute to strength development have been proposed for modelling in the literature: ‘intimate contact’ (step 1-3) and ‘healing’ (step 4-5) [169,170].

Intimate contact describes the amount of surface area that is physically in contact between the interface of both parts at any time [170]. **Healing** refers to the interdiffusion of polymer molecules across the interface [170], which is the determining factor for strength development. As full surface contact is a premise to allowing the interdiffusion of the molecules, both

mechanisms have to be considered for a successful fusion bond [170]. Both mechanisms have been studied extensively and theoretical models have been proposed in public literature [113,169–171,173–176] of which a short review is given below.

5.5.1.1 Intimate contact

When two surfaces of the parts to be joined are brought together, only a fraction of the surface area is in contact, since materials never have perfectly smooth surfaces and contain surface asperities. Intimate contact is dependent on the surface roughness, which can be changed by temperature and pressure. By applying temperature and pressure, the materials soften, the asperities can be deformed and the amount of surface area increased [170]. In literature intimate contact is modelled by different researchers [174–176] and the degree of intimate contact D_{ic} is defined as the fraction of the total surface that is in contact. In these models the surfaces are idealised and described by a wave of rectangular elements [174–176]. The latest model, the Mantell-Springer model [174], assumes that rectangular elements representing the irregular surface are deformed by pressure, as shown schematically by the dashed line in Figure 42.

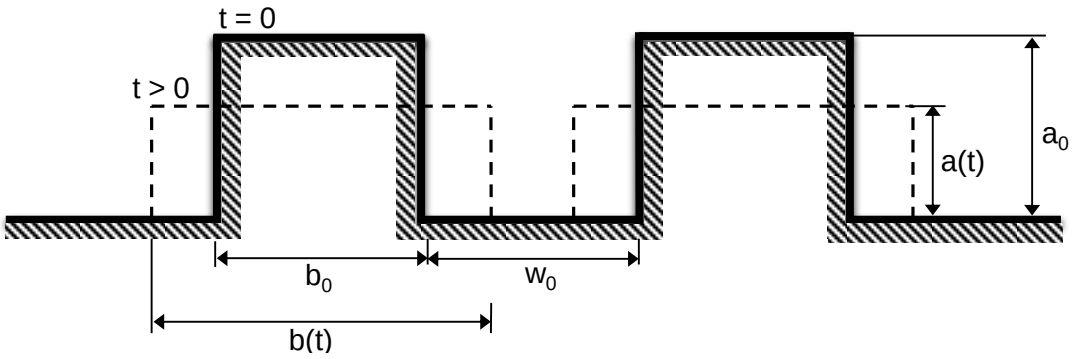


Figure 42: Schematic illustration of the deformation of surface asperities according to Mantell et al. [174]

This model [174] accounts for time-varying material properties and conditions. The degree of intimate contact D_{ic} is therefore expressed by

$$D_{ic} = \frac{b(t)}{w_0 + b_0} \qquad \textbf{Equation 4}$$

where b_0 is the width of the initial rectangular elements, w_0 the initial width between the rectangular elements and $b(t)$ the width after the time t of deformation. Furthermore, a_0 is the initial height of the elements and $a(t)$ the height after deformation, see Figure 42. Based on the assumption that the element volume remains constant and with the law of conservation of mass, the degree of intimate contact can be expressed according to [174] as

$$D_{ic} = \frac{1}{1 + \frac{w_0}{b_0}} \left[1 + 5 \left(1 + \frac{w_0}{b_0} \right) \left(\frac{a_0}{b_0} \right)^2 \int_0^{t_p} \frac{p_{app}}{\eta} \, dt \right]^{1/5} \qquad \textbf{Equation 5}$$

where η is the polymer viscosity, p_{app} the applied pressure, a_0 the initial height of the rectangular element and t_p the time of the pressure application.

5.5.1.2 Healing

When two thermoplastic materials are brought into contact above the glass transition temperature for amorphous polymers or the melting temperature for semi-crystalline polymers (below these temperatures molecular interdiffusion is restricted due to lack of polymer mobility), interdiffusion of polymer chain segments back and forth across the interface takes place [169,170]. The interface of the materials to be joined disappears (it 'heals') and after a certain period the bulk material properties of the polymer can be achieved. The motion of a polymer chain in an amorphous material has been modelled by DeGennes [134] with the following equation:

$$\frac{l}{L} = \left(\frac{t}{T_r}\right)^{\frac{1}{2}}$$ **Equation 6**

where *L* is the length of the fictitious tube in which the polymer chain is confined, *l* the polymer chain end that exits the tube, *t* the time and the reptation time T_r, when the chain has totally exited the original tube *(l=L)*, see Figure 43 [169]. The motion of a polymer chain depends on the polymer chain characteristics such as weight average molecular weight (Mw).

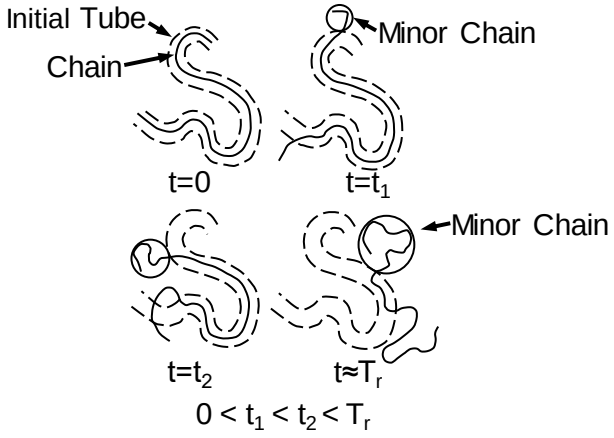


Figure 43: Model of motion of polymer chains according to Bastien et al. [169]

Regarding interdiffusion, it is possible to define an average interpenetration distance *χ* (Figure 44) of the chains across the interface, which varies with the square root of the minor chain length *l* [113]. *χ* is then described as:

$$\frac{\chi}{\chi\infty} = \left(\frac{l}{L}\right)^{1/2} = \left(\frac{t}{T_r}\right)^{1/4}$$ **Equation 7**

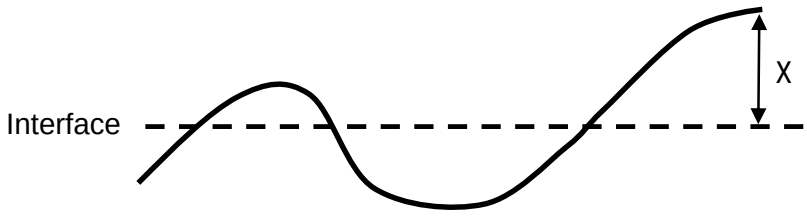


Figure 44: Definition of interpenetration distance of polymer chains

The healing theory [113,172] derives the mechanical properties ‘strength’ and ‘toughness’ from the parameters *l* and *χ*, by making assumptions on two failure mechanisms: chain pull-out and chain breakage. For both failure mechanisms, the time dependence on the fracture stress σ and energy G_c is the same and the relations can be expressed as:

$$\frac{\sigma}{\sigma_\infty} = \left(\frac{t}{T_r}\right)^{1/4} \quad \textbf{Equation 8}$$

$$\frac{G_c}{G_{c\infty}} = \left(\frac{t}{T_r}\right)^{1/2} \quad \textbf{Equation 9}$$

where σ_∞ and $G_{c\infty}$ are the fracture stress and fracture energy of the fully healed interface, which is achieved at $t=T_r$. The relations are valid for isothermal conditions at a temperature T. For a non-isothermal process, the process time t_p can be divided into q time intervals $(t_{i+1} - t_i = \Delta t = t/q)$ in which the temperature T_i^* is assumed to be constant [169]. This leads to the following equation

$$\frac{\sigma}{\sigma_\infty} = \sum_{i=0}^{t_p/\Delta t} \frac{t_{i+1}^{1/4} - t_i^{1/4}}{T_r^{*1/4}} \quad \textbf{Equation 10}$$

$$\frac{G_c}{G_{c\infty}} = \left[\sum_{i=0}^{t_p/\Delta t} \frac{t_{i+1}^{1/4} - t_i^{1/4}}{T_r^{*1/4}}\right]^2 \quad \textbf{Equation 11}$$

where T_r^* is the reptation time at the temperature T_i^*. The degree of healing D_h is represented by the ratio of the achieved strength σ by healing and the maximum realisable strength of the material σ_∞:

$$D_h = \frac{\sigma}{\sigma_\infty} \quad \textbf{Equation 12}$$

5.5.1.3 Coupled model

Different approaches can be found in public literature irrespective of whether intimate contact or healing governs the bonding process, depending on the processing parameters. For instance at high temperatures above the glass transition or melting temperature, healing occurs instantaneously, therefore intimate contact is the governing mechanism $(t_{healing} < t_{intimate\ contact})$ [52,169,177]. At lower temperatures the time to obtain full strength $(D_h = 1)$ is much longer than the time to achieve full intimate contact $(D_{ic} = 1)$, therefore healing governs the process $(t_{healing} > t_{intimate\ contact})$ [169,178]. Other approaches are also available where both models are combined since healing can only occur across areas where intimate contact is already achieved at the interface [6,170,179,180]. Therefore, the degree of bonding D_b is the result of a combination of the degree of intimate contact and the degree of healing, for which Butler et al. [170] proposed a model and thereby provides a more realistic description of the fusion bonding process than by considering the mechanisms independently. In the model, it is considered that only the contact area can heal. The area of contact where healing can take place is increased by applying pressure for a certain time. The degree of bonding D_b is defined as:

$$D_b = D_{ic}(0) * D_h + \int_0^t D_h\,(t - t') * \dot{D}_{ic}(t')dt' \qquad \textbf{Equation 13}$$

The lead term accounts for healing over the area initially in contact D_{ic} *(0)*. The derivative of D_{ic} accounts for the new area that has come in contact during the time interval *t'* to *t' + dt.* The quantity D_h*(t-t')* is the amount of healing that has occurred over the new area that has been in contact for a time *t-t'*.

5.5.2 Bonding model deduction

The prediction of the tensile bond strength between CF/PEEK skins, which are superficially enriched with the PEI layer, and a PEI foam core, is the focus of the current study. As shown in chapter 5.1 the process window is constrained due to skin de-consolidation and core collapse at higher temperatures (*T* > 343 °C). This means that temperatures below the usual PEI processing temperatures (~370 °C [153]) are recommended during the fusion bonding process to prevent skin de-consolidation. In addition, the PEI foam possesses a rough surface. Therefore, in this study both intimate contact and healing mechanisms are considered. In addition, the bonding process occurs under highly non-isothermal conditions since the non-isothermal compression moulding process is selected as manufacturing technique (refer 4.3).

To predict the bond strength *σ(t)* for the CF/PEEK-PEI foam sandwiches, the modelling approach by Butler et al [170] is applied. By combining Equation 4, Equation 5, Equation 10 and Equation 13 and dividing the process time t_p into *q* time intervals in which the temperature *T* and the viscosity *η* are approximately constant, the bond strength can be calculated by:

$$\sigma(t_i) = \sigma_\infty * \sum_{i=1}^{t_p/\Delta t} \left[\left(\frac{b_0}{b_0 + w_0} \right) * \frac{t_{i+1}^{\frac{1}{4}} - t_i^{\frac{1}{4}}}{T_r^{*\frac{1}{4}}} + \left(\frac{b(t_i)}{b_0 + w_0} - \frac{b_0}{b_0 + w_0} \right) * \frac{t_{i+1}^{1/4} - t_i^{1/4}}{T_r^{*1/4}} \right] \qquad \textbf{Equation 14}$$

with

$$b(t_i) = a_{t_{i-1}} b_{t_{i-1}} \left[\frac{1}{a_{t_{i-1}}^5} + 5\, \frac{p_{app}\left(b_{t_{i-1}} + w_{t_{i-1}}\right)}{\eta(t_i) a_{t_{i-1}}^3 b_{t_{i-1}}^3} (t_i - t_{i-1}) \right]^{1/5} \qquad \textbf{Equation 15}$$

and

$$a_{t_i} = \frac{a_{t_{i-1}} b_{t_{i-1}}}{b_{t_i}} \qquad \textbf{Equation 16}$$

$$w_{t_i} = b_{t_{i-1}} + w_{t_{i-1}} - b_{t_i} \qquad \textbf{Equation 17}$$

5.5.3 Determination of model input parameters

To predict the bond strength according to Equation 14, input for the following parameters is needed:

1. Process parameters: Interface temperature *T* and Process time t_p during the compression moulding process, Applied pressure p_{app}
2. Material properties: Reptation time T_r, Surface roughness a_0, b_0, w_0, Viscosity *η*, Tensile strength σ_∞

In the following sections the input parameters are determined.

5.5.3.1 Interface temperature T and process time t_p

The temperature T with time of the skin-to-core interface during processing is of major importance as it allows prediction of polymer mobility which enables polymer flow to achieve intimate contact and interdiffusion. Therefore, prediction of temperature evolution at the interface is necessary in order to determine the process time t_p as well as to supply input for reptation time T_r and the viscosity η in Equation 14 and Equation 15. Both are highly dependent on the process temperature.

To describe the heat transfer from the heated skins into the foam core a simplified non-isothermal heat transfer model is used. The model is based on the manufacturing process which is schematically illustrated in Figure 45. Here, the focus lies on the heat transfer from skins into the core by means of heat conduction.

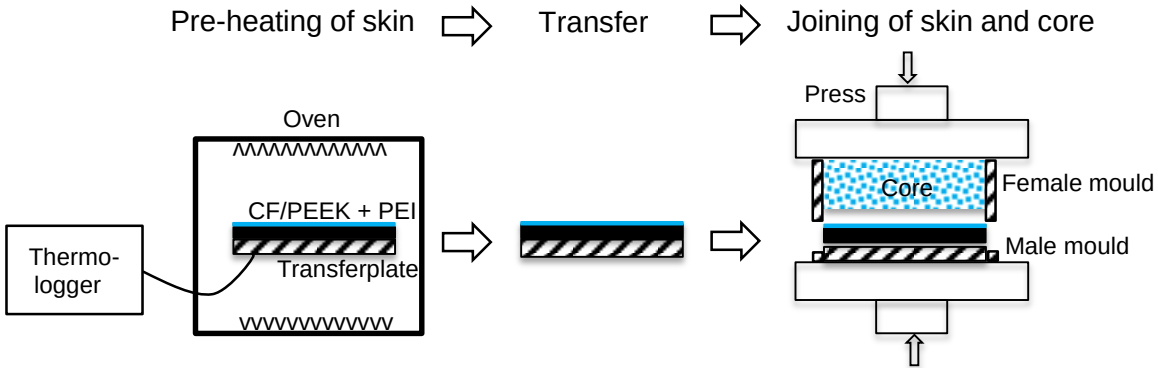


Figure 45: Non-isothermal compression moulding process

This process contains the following steps:

Heating: The skin is placed on a transfer plate and heated in an oven until it reaches the pre-determined skin pre-heat temperature $T_{Skin\ pre\text{-}heat}$.

Transfer: Skin and transfer plate are transferred into the press and integrated into a male mould. The transfer takes around 10 - 15 seconds and the heat loss during transfer is ~1.5 °C/sec. Pre-trials showed that the application of a transfer plate is necessary to reduce loss during transfer (more details in chapter **Fehler! Verweisquelle konnte nicht gefunden werden.**).

Pressing: The cold or pre-heated core is already positioned in the female mould which is installed on the upper press platen. Once transfer plate and skin are integrated into the male mould, the mould is closed and pressure is applied.

In this process the temperature evolution at the interface $T_{Interface}$ is mainly dependent on the skin pre-heat temperature $T_{Skin\ pre\text{-}heat}$, transfer plate pre-heat temperature $T_{Transfer\ plate}$, core temperature T_{Core} as well as on temperatures of the periphery (e.g. press). The temperature evolution of the interface $T_{Interface}$ can be described dependent on the time t and the location (x,y,z) by applying a non-isothermal heat transfer equation [181].

$$\rho c \frac{\partial T}{\partial t} = \left[\frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda \frac{\partial T}{\partial z}\right)\right] + \dot{\Phi}''' \qquad \textbf{Equation 18}$$

where λ is the thermal conductivity, ρ the density, c the specific heat capacity and Φ''' the heat generation (e.g. exothermal reactions). Equation 18 can be simplified for a two-dimensional case and without the additional heat generation to:

$$\rho c \frac{\partial T}{\partial t} = \left[\frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda \frac{\partial T}{\partial y}\right)\right] \qquad \textbf{Equation 19}$$

The finite difference method is implemented to solve the numerical approach, where the derivatives are substituted by differential quotients. This leads to:

$$\frac{T_{m+1,n}^{i+1} - 2\,T_{m,n}^{i+1} + T_{m-1,n}^{i+1}}{(\Delta x)^2} + \frac{T_{m,n+1}^{i+1} - 2\,T_{m,n}^{i+1} + T_{m,n-1}^{i+1}}{(\Delta y)^2} = \frac{\rho c}{\lambda}\frac{T_{m,n}^{i+1} - T_{m,n}^{i}}{\Delta t} \qquad \textbf{Equation 20}$$

where $T_{m,n}^{i+1}$ is the temperature for the time point *i+1* after the time step Δt. Δx and Δy are the distances between two nodes, which are labelled with *m* und *n* (refer Figure 46).

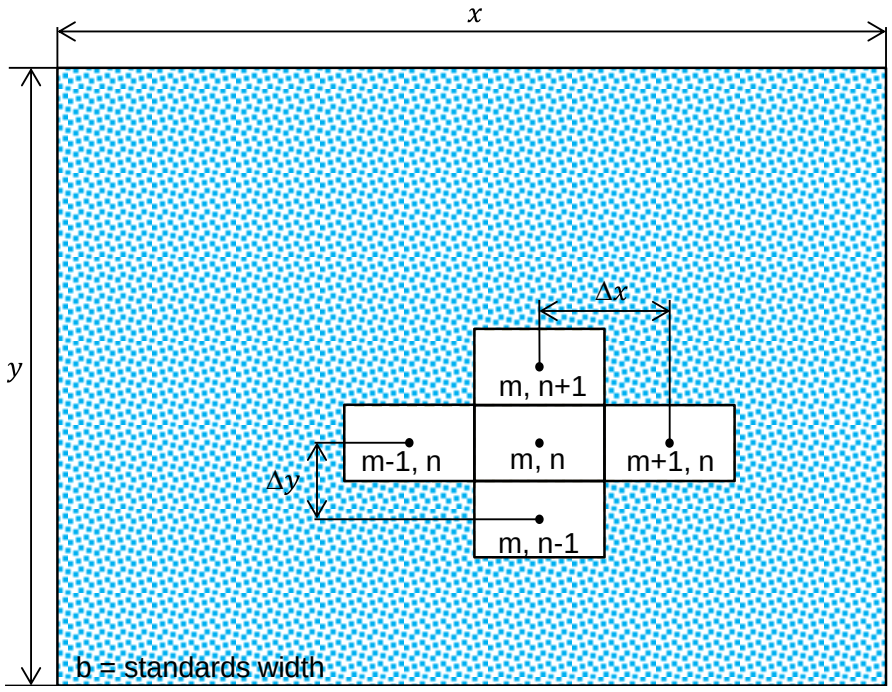


Figure 46: Arrangement of elements and nodes

Reordering Equation 20 leads to the energy balance equation of every node

$$\frac{\lambda\,\Delta y}{\Delta x}\left(T_{m+1,n}^{i+1} - T_{m,n}^{i+1}\right) + \frac{\lambda\,\Delta y}{\Delta x}\left(T_{m-1,n}^{i+1} - T_{m,n}^{i+1}\right) + \frac{\lambda\,\Delta x}{\Delta y}\left(T_{m,n+1}^{i+1} - T_{m,n}^{i+1}\right) + \frac{\lambda\,\Delta x}{\Delta y}\left(T_{m,n-1}^{i+1} - T_{m,n}^{i+1}\right) = \frac{1}{\tau}\left(T_{m,n}^{i+1} - T_{m,n}^{i}\right) \qquad \textbf{Equation 21}$$

with

$$\tau = \frac{\Delta t}{\Delta x\,\Delta y\,c_p\,\rho} \qquad \textbf{Equation 22}$$

A relation between the individual energy balances of every volume element is achieved by the multiplication of a coefficient-matrix $\underline{A}$ and the temperatures

$$\underline{\boldsymbol{A}} \times \boldsymbol{T}_{i+1} = \boldsymbol{T}_i. \qquad \textbf{Equation 23}$$

In order to reduce the modelling extent, the following assumptions are taken into account:

- Skins and transfer plate are uniformly heated in a convection oven
- The core is kept at room temperature or heated up uniformly
- Skins and transfer plate cool down ~20 °C during transfer from the oven into the press (driven by convection and emissions)
- The model is effective after the press is closed and press platen, transfer plate, skin and core are in full contact.
- From here T_{Skin} is referred to as the temperature of the skin in the press
- The model is implemented for one skin and the core up the core centre (mirror-line) because of the symmetric setup
- Heat loss to the environment at the periphery of the skins is neglected since the area of the skins is much larger than the thickness of the skins and transfer plate
- After several repetitions of the process, the press surface will warm up. This influences the heat transfer and might influence the bond strength development. However, for this study it is neglected and the surface press temperature is assumed to be at room temperature for every trial.
- Material properties (specific heat capacity, density, heat conductivity, etc.) are considered to be constant for a material phase
- The core area adjacent to the skin collapses at temperatures above $T_g(PEI)$ and from then material properties are considered to be valid for a bulk PEI material
- The periphery is considered to be adiabatic

Figure 47 displays the manufacturing setup for the implementation of the heat model, with

- dx = node distance in x-direction
- h_P = Height of press
- dh_P = Node distance (Press elements)
- h_T = Height of Transfer plate
- dh_T = Node distance (Transfer plate elements)
- h_S = Height of Skin
- dh_S = Node distance (Skin)
- h_c = Height of core
- dh_c = Node distance core (Core)
- $dh_{c,small}$ = Node distance (Core, when compacted)

The values for the dimensions as well as material properties for the press, transfer plate, skin, core and compacted core material are given in Appendix A.

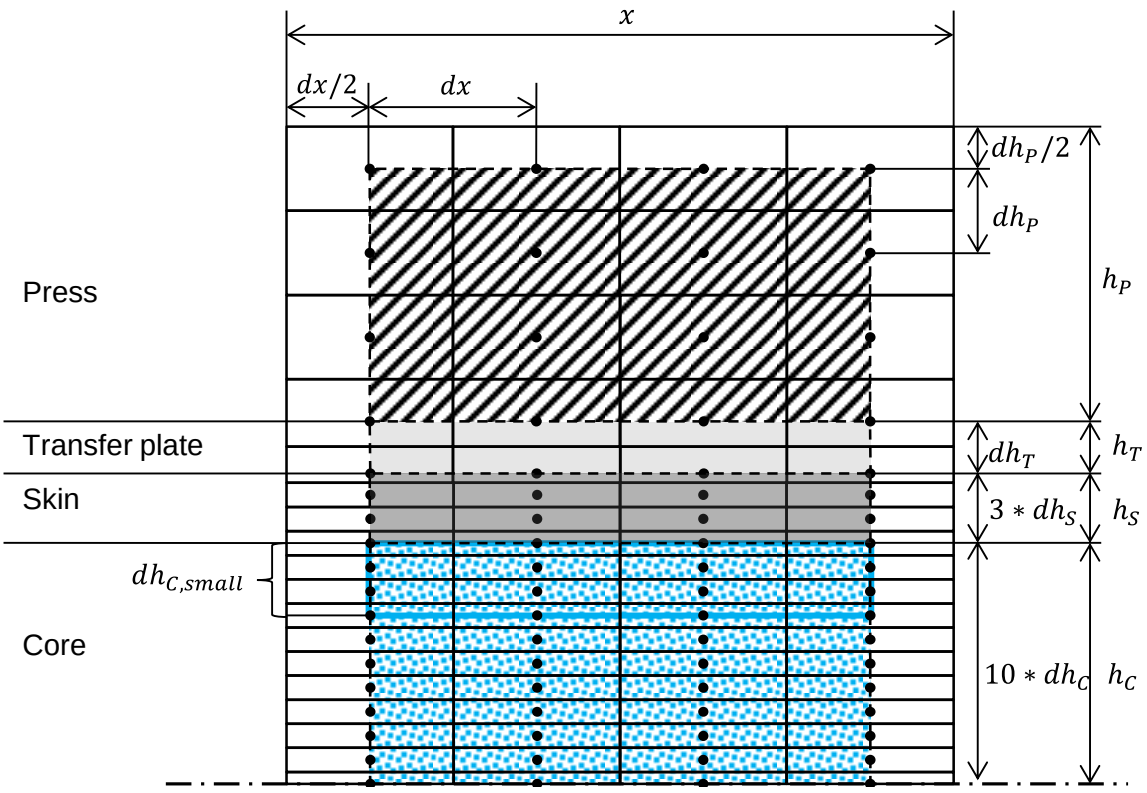


Figure 47: Discretisation of manufacturing setup

By formulating the energy balance for every element, the input of the boundary conditions and material data in Appendix A, Equation 23 can be solved and the temperature evolution with time at the interface predicted.

Experimental trials are conducted to validate the heat transfer model results. Thermocouples (Typ K, GG-KI-36-SLE-(*), Ø = 0.13 mm by Omega Engineering, Germany) are integrated into the skins, below the core surface (~1 mm below the core surface) as well as into the core centre (~2 mm – ~5 mm) and the temperature evolution of skins, core surface and core centre is recorded, see Figure 48. Due to the wire diameter and the manual integration, a hundred percent exactness of positioning cannot be assured, which can lead to deviations.

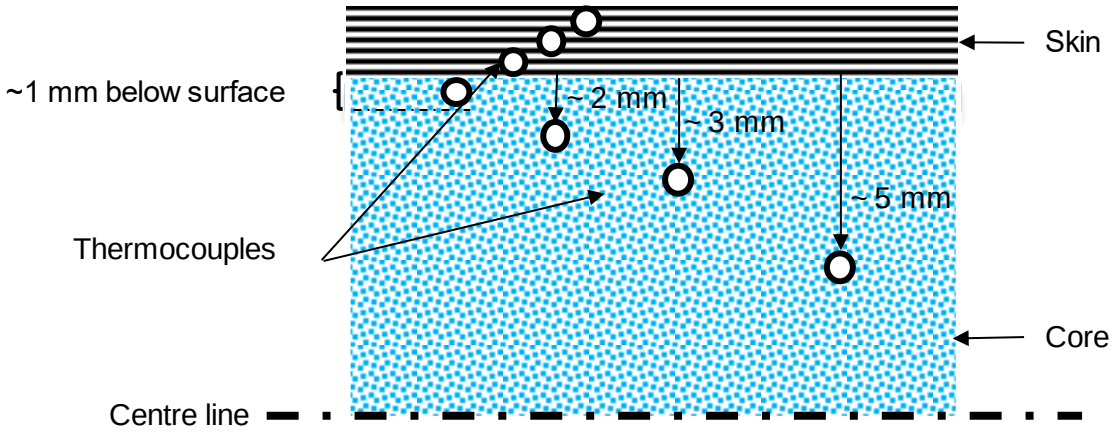


Figure 48: Integration of thermocouples to monitor heat flow from skin into core

Figure 49 shows a comparison of the predicted (dashed lines) and the experimentally determined (solid lines) temperature evolution for the skin, the core just below (~1 mm) the surface as well as for the core centre at different core depths. For purpose of simplification, the illustration of temperature evolution of the transfer plate and the periphery is omitted. The skin is pre-heated in an air-circulating oven to a temperature of 330 °C ($T_{Skin\ pre\text{-}heat}$). The core is kept at room temperature. As the model is valid after the press is closed (see assumptions), where all parts are in close contact, the prediction starts with a temperature of 310 °C for the skin (T_{Skin}). The temperature difference is related to the heat loss during transfer from the oven into the press, which is neglected in the model.

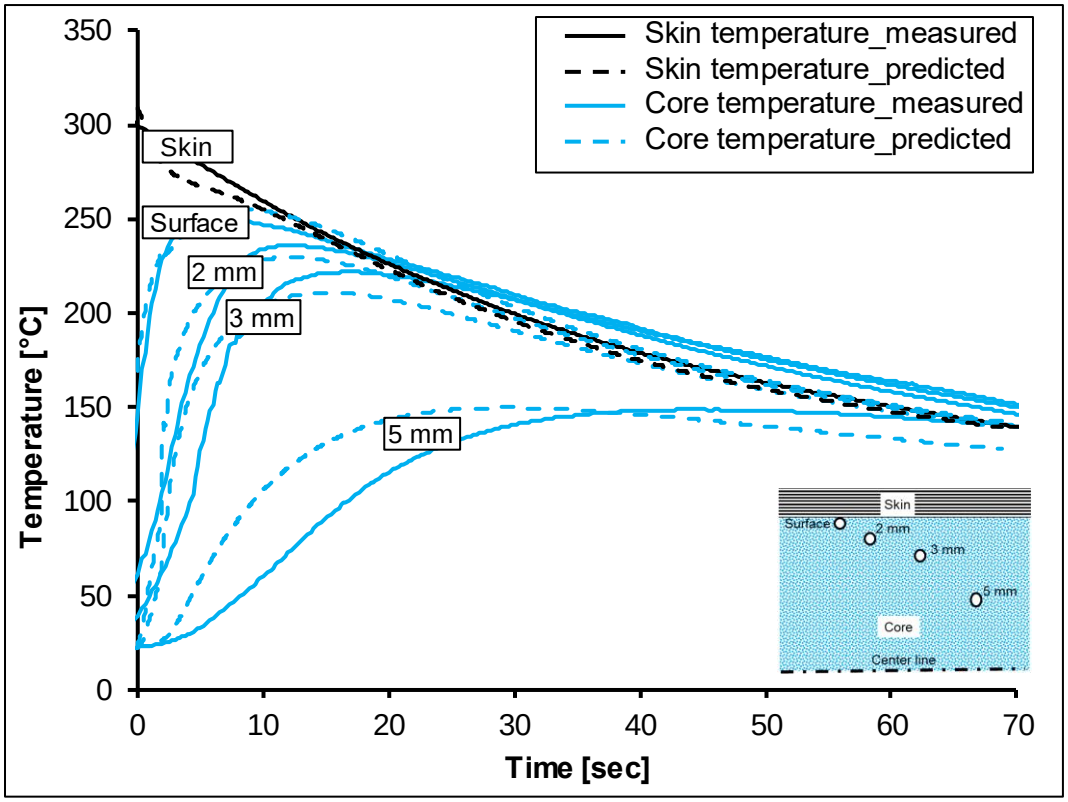


Figure 49: Temperature evolution (predicted and measured) of skin and core (at different core depths) for T_{Skin} = 310 °C and T_{Core} = 23 °C

Figure 49 shows that there is a reasonable agreement between predicted and measured temperature evolutions. Slight deviations between predicted and measured temperatures can be attributed to the assumptions (adiabatic periphery, material properties) in the model and inaccuracy of the thermocouple location. The higher starting temperatures of the measured temperature graphs can be explained by the heat conduction from the skin into the core before the press is fully closed. The unsteadiness of the predicted temperature profile of the core during the heating phase can be ascribed to the change of material properties between solid and softened aggregate state as well as core compaction which is considered by a change of the cell size in the model.

Since only the temperature evolution of the interface is relevant for the bond strength prediction, further temperature evolution graphs are simplified with focus on temperature

evolution of the skin and interface, see Figure 50. Here, the interface temperature is defined as an average temperature of skin and core surface temperatures.

In order to ensure correctness and reproducibility of the results, temperature measurements have been conducted multiple times and deviations during processing are determined, which are displayed with the red bandwidth in Figure 50. Except for the difference of the starting temperatures (caused by heat conduction from the skin into the core before the press is fully closed) the predicted temperature profile conforms to the measured temperature profile. A satisfying agreement between the temperature evolution prediction and measured temperature evolution is achieved. Therefore, the predicted temperature evolution depending on the skin and core temperature is used to supply input for the process time t_p in Equation 14 and for the reptation time T_r (see following section) in the fusion bond modelling approach.

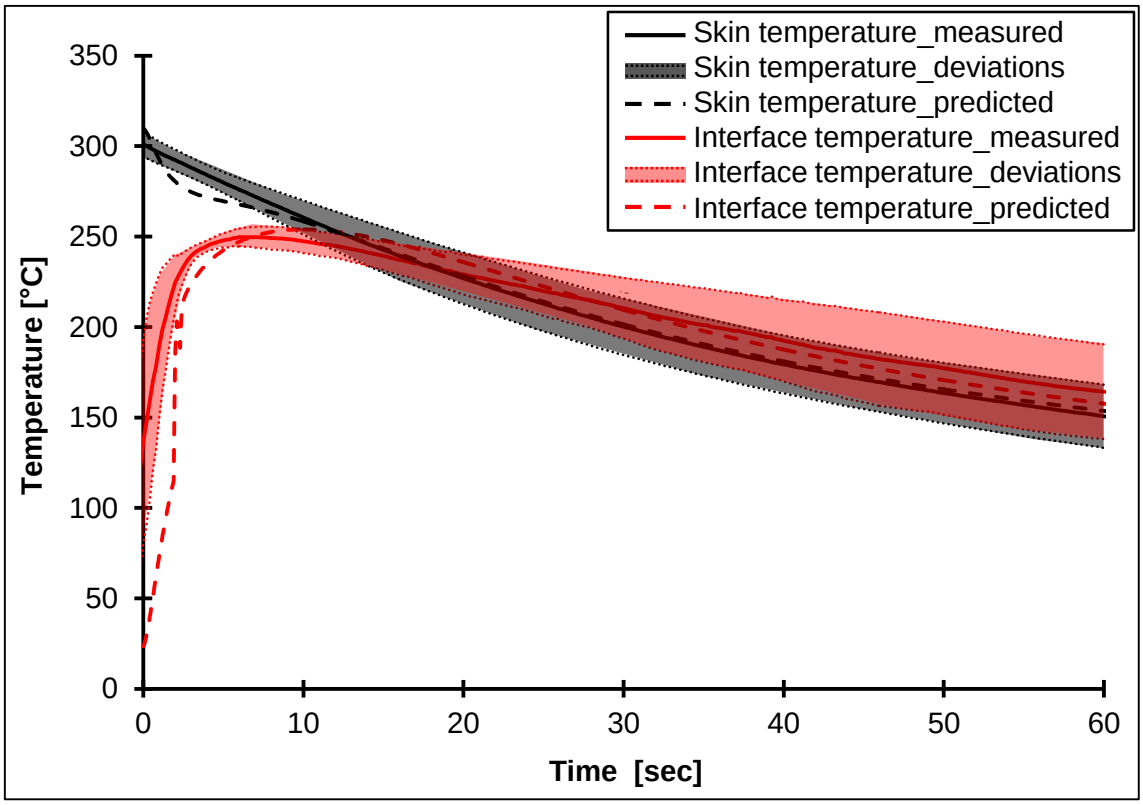


Figure 50: Skin and interface temperature evolution (predicted and measured) for T_{Skin} = 310 °C and T_{Core} = 23 °C

5.5.3.2 Applied pressure p_{app}

The pressure influences the time to achieve intimate contact, while the healing process runs pressure-independent. In contrast to fusion bonding of reinforced thermoplastic monolithic parts or thermoplastic bulk materials, foam cores are sensitive to pressure under elevated temperatures. In order to minimise the risk of core crushing under load, a low pressure (p or p_{app}) of 0.2 MPa is chosen for all manufacturing trials and not further investigated. The pressure of 0.2 MPa is lowest pressure realisable with the available manufacturing equipment.

5.5.3.3 Reptation time T_r

For the fusion bonding process, the reptation time T_r represents the time which is needed to achieve a fully healed interface, which has properties equaling the bulk material. Therefore, the reptation time T_r is a key parameter for the prediction of the bond strength according to Equation 14 and therefore the reptation time of PEI $T_r(PEI)$ is of great interest to this study. T_r is a material depend parameter, which needs to be determined individually for every envisaged material. For the sandwich case, Bastien et al. [169] already investigated the reptation time for amorphous polymers, specifically for PEI, during non-isothermal processing based on the minor chain length l and the interpenetration distance χ. Bastien et al. showed that the average interpenetration distance χ of the polymer chain across the interface is the most representative model to predict the bond strength for non-isothermal processes [169]. By experimental trials the reptation time for PEI was defined dependent on different temperatures, see Figure 51.

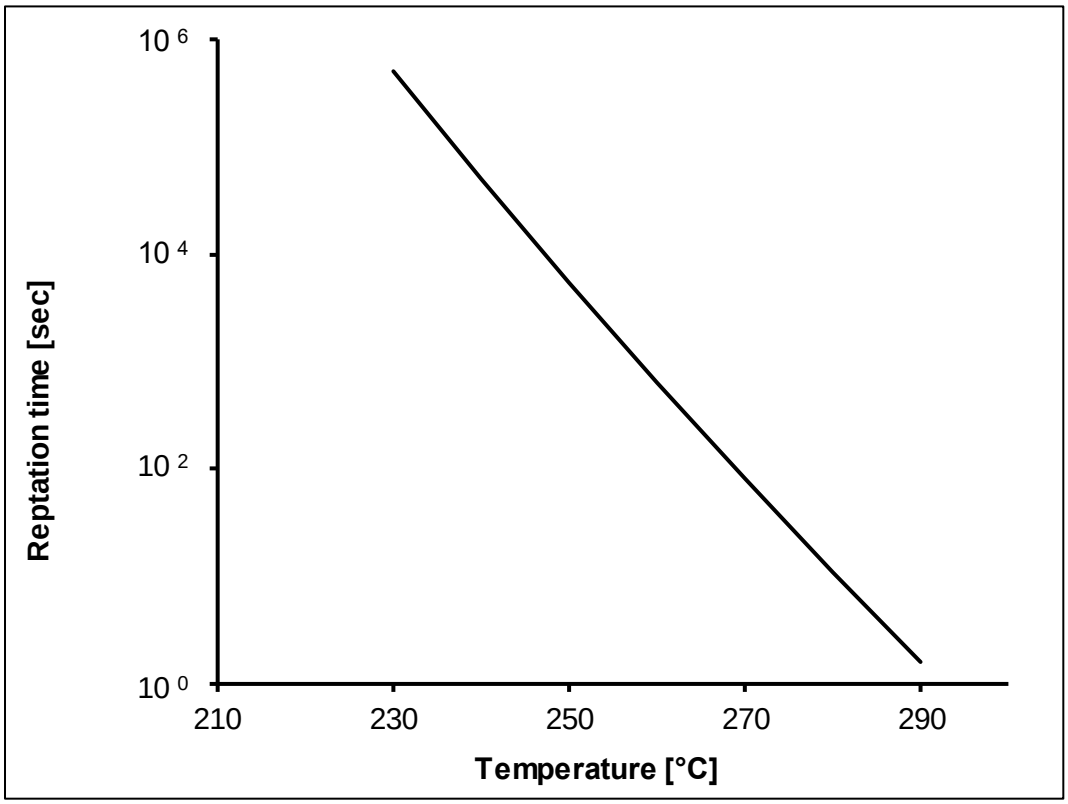


Figure 51: Reptation time for PEI depending on the temperature according to Bastien et al. [169]

As shown in Figure 51 the reptation time is highly dependent on the temperature. For the implementation of the bond strength model, the reptation time of PEI $T_r(PEI)$ must be related to the interface temperature T with time, which is described by the heat transfer model.

5.5.3.4 Surface roughness

In [182] it is considered that the rougher surface of the parts to be joined is the limiting surface to achieve intimate contact. For the bonding process in this study, it is therefore assumed that the PEI surfaces of the skins are very smooth compared to the foam core surfaces. The time needed for flattening of the core surface is the limiting parameter for the development of

intimate contact between the PEI surface of the skins and core. The surface roughness of the foam core is therefore experimentally characterised using a DektakXT® stylus profiler by Bruker, Billerica Massachusetts, USA. Figure 52 shows a representative surface profile of the initial PEI foam core.

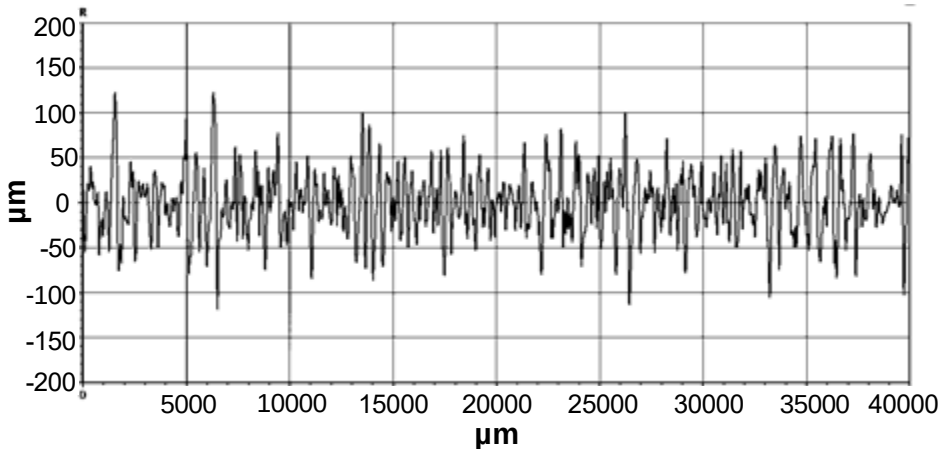


Figure 52: Representative surface profile of the PEI foam

The obtained surface profile is fitted to the idealised surface model of Mantell and Springer [174] leading to the required values a_0, b_0, w_0 (see Table 16) in Equation 14, Equation 15, Equation 16 and Equation 17.

Table 16: Values of the idealised PEI foam surface

Parameter	**a_0**	**b_0**	**w_0**
Value [µm]	26.98	174.49	171.74

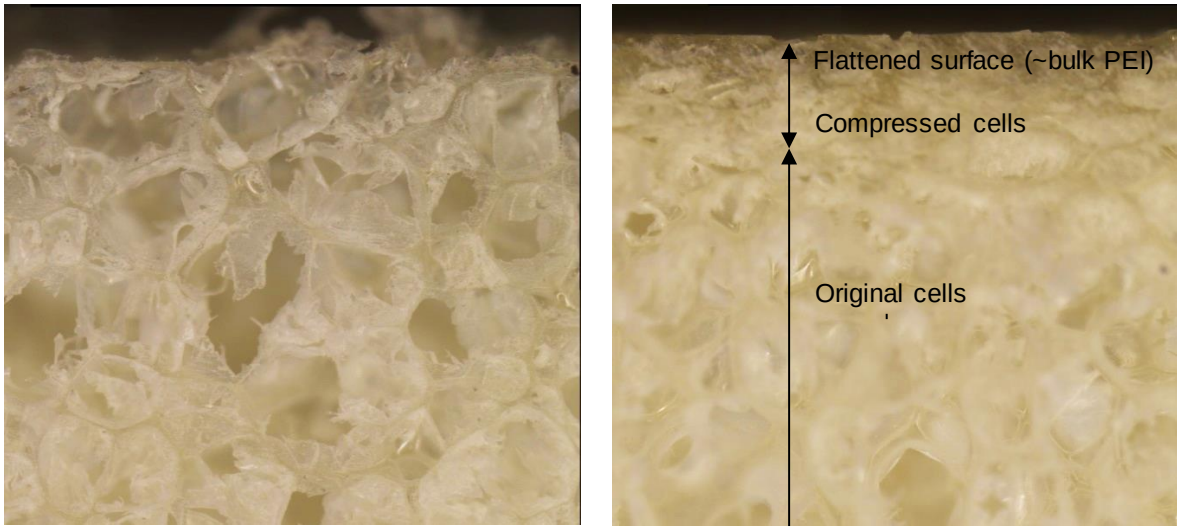
It is assumed that during processing the surface roughness is changed by means of pressure even before PEI is softened by temperature above its T_g. Due to the low-density structure of the core, the surface asperities might be reduced and flattened plastically by means of the pressure and elevated temperatures, which are close to but albeit below the T_g. To verify this, the initial foam is compacted in a trial at temperatures of 200 °C and 210 °C (temperatures close to the $T_g(PEI)$) for 1 second under a pressure of 0.2 MPa. Figure 53 shows the plastic change of the PEI foam surface between the initial foam (Figure 53a) and the compressed foam at a temperature of 210 °C, see Figure 53b.The compaction of the foam surface leads to a densified material structure which can be compared to bulk material.

Table 17 presents the measured surface roughness of the initial PEI foam surface and PEI foam surfaces treated with 200 °C and 210 °C under 0.2 MPa for 1 second.

Table 17: Measured PEI foam surface profiles

Temperature [°C]	Pressure [MPa]	a_0 [µm]	b_0 [µm]	w_0 [µm]
23	/	26.98	174.49	171.74
200	0.2	8.58	145.41	99.30
210	0.2	5.91	130.59	87.23

Since these results show that the surface of the foam core is already flattened and presumably thereby the contact area increased before the materials softens above T_g, the surface roughness parameters $a_0(210\ °C)$, $b_0(210\ °C)$, $w_0(210\ °C)$ and not $a_0(23\ °C)$, $b_0(23\ °C)$, $w_0(23\ °C)$ are taken as the starting input parameters for the bond strength model in Equation 14, Equation 15, Equation 16 and Equation 17.



a) b)

Figure 53: Microscopic picture of the surface of a) an initial PEI foam and b) a PEI foam after treatment with 210 °C, 0.2 MPa for 1 sec

5.5.3.5 Viscosity

In general, the viscosity depends very much on the shear velocity, temperature and on several polymer characteristics such as molecular weight [183]. However, for low shear velocities of polymers, which is assumed to be valid for compression moulding, shear velocity can be neglected. In this case the polymer melt can be treated as a Newtonian fluid. The viscosity of PEI is determined by means of rheometric analysis and can be empirically described as

$$\eta_{PEI}(T) = 2 * 10^{34} * T^{-12.03} \qquad \textbf{Equation 24}$$

Combined with the temperature evolution during processing at the interface, the viscosity of PEI during fusion bonding can be described for every time interval and used in Equation 14.

5.5.3.6 Tensile strength σ_∞

This study aims to predict the tensile strength of the interface, since it can be compared with the tensile strength of the core, which enables a statement on which part of the sandwich will

be the weakest link. During the fusion bonding process the surface of the foam is softened and compressed with the result that ‘bulk’ material at the surface is formed, see Figure 53b. This means that a bulk PEI skin surface (PEI film) is joined to a ‘bulk’ PEI foam surface with the aim to achieve a fully healed PEI bulk material. Therefore, for the prediction of the skin-to-core tensile bond strength according to Equation 14, the reference tensile strength $\sigma_\infty = \sigma_{Tensile}$ (PEI) = 105 MPa [157] of a fully healed PEI bulk material is used.

5.6 IMPLEMENTATION OF BOND MODEL

According to Equation 14 the tensile bond strength can be predicted depending on the process parameters and material properties, quantities that have been determined in the previous section. In this theoretical study, the focus is on the investigation of the interface temperature influence on the bond strength of sandwich specimens.

5.6.1 Parameter definition

The interface temperature can be influenced by heating the parts to be joined, namely the skins as well as the core. As presented in chapter 5.1, the process window for joining CF/PEEK skins and the PEI core is narrow since extensive heating (T_{Skin} > 340 °C) leads to skin de-consolidation and to core collapse. Lower temperatures (T_{Skin} < 230 °C) do not enable fusion bonding based on the healing theory (refer to Figure 51). Therefore, in consideration of heat loss during transfer, the bond strength is to be predicted for skin temperatures (T_{Skin}) between 260 °C and 320 °C in steps of 10 °C and core temperatures (T_{Core}) of room temperature (T_R = 23 °C), 100 °C and 200 °C. A core temperature of 200 °C is considered the maximum possible core pre-heat temperature (in consideration of heat loss during transfer) since core collapsing was observed at core temperatures above T_g of the core. The pressure for manufacturing is kept constant at a low level of 0.2 MPa to avoid extensive core compaction.

In the following section the results are presented and discussed. Here, the predicted tensile strength is normalised to the strength of a fully healed interface $\bar{\sigma} = \frac{\sigma}{\sigma_\infty} * 100\,\% = \frac{\sigma}{\sigma_{\mathrm{T(PEI)}}} * 100\,\%$.

Furthermore, the results are compared to the tensile strength of the core, which was characterised according to DIN53292 (chapter 5.7.2.2) and determined to be 2.64 % (also normalised to the bulk material strength). As a result, sandwiches featuring a predicted tensile strength below 2.64 % of the reference tensile strength σ_∞ are expected to fail adhesively (Adh) within the interface, while sandwiches with a predicted normalised tensile strength above 2.64 % will probably fail cohesively (Coh) within the core, based on the assumption of the weakest link.

5.6.2 Bond strength prediction depending on skin temperature

The temperature of the skins influences the bond strength to a large extent because the skins supply most of the heat energy to soften the polymer and to enable molecular mobility to achieve intimate contact and to allow polymer interdiffusion.

As an example, Figure 54 shows the calculated temperature with time for a skin laminate temperature of 260 °C and the interface temperature with time, as well as the predicted normalised tensile bond strength. The core is thereby kept at room temperature. Since the

temperature of the interface stays relatively low (~230 °C), where the motion of the molecules is slow and the reptation time is high, the predicted tensile bond strength is low. The model predicts a normalised tensile bond strength, which is 0.56 % of the bulk PEI tensile strength. The prediction of the normalised strength of 0.56 % means that the sandwich will feature an insufficient (lower than the core strength) bond quality and that the sandwich will probably fail within the interface, since the core itself features a normalised tensile strength of 2.64 % in.

In comparison, Figure 55 exemplarily displays the predicted normalised tensile bond strength based on the temperature evolution for a skin temperature of 310 °C. Due to the higher temperature of the skins, the interface temperature is increased up to approximately 260 °C, where interdiffusion of the polymers occurs to a larger extent (T_r ~ 639 sec). Therefore, the model predicts that the bond quality is improved and the sandwiches feature a normalised tensile bond strength of approximately 7.85 % in comparison to the reference tensile strength. Since the normalised tensile strength of the core is around 2.64 %, the model predicts that the bond quality is sufficient (not the weakest link), albeit low in comparison to the bulk material strength, and failure of the sandwich will occur within the core.

Table 18 summarises the predicted normalised bond strength for skin temperatures in the range 260 °C – 320 °C. For all predictions, the core temperature is kept at room temperature. In addition, a prognostication about the expected failure mechanisms is given.

Table 18: Predicted normalised bond strength and failure mechanisms for different skin temperatures

T_{Skin} [°C]	260	270	280	290	300	310	320
Predicted $\bar{\sigma} = \frac{\sigma}{\sigma_\infty}$ [%]	0.56	1.34	2.2	3.35	5.05	7.85	13.13
Expected failure mechanism [Adh/Coh]	Adh	Adh	Adh	Coh	Coh	Coh	Coh

From Table 18 it becomes clear that the model predicts that sandwiches manufactured with skin temperatures above 290 °C and a core kept at room temperature will feature sufficient bond strength, since a cohesive failure within the core is prognosticated.

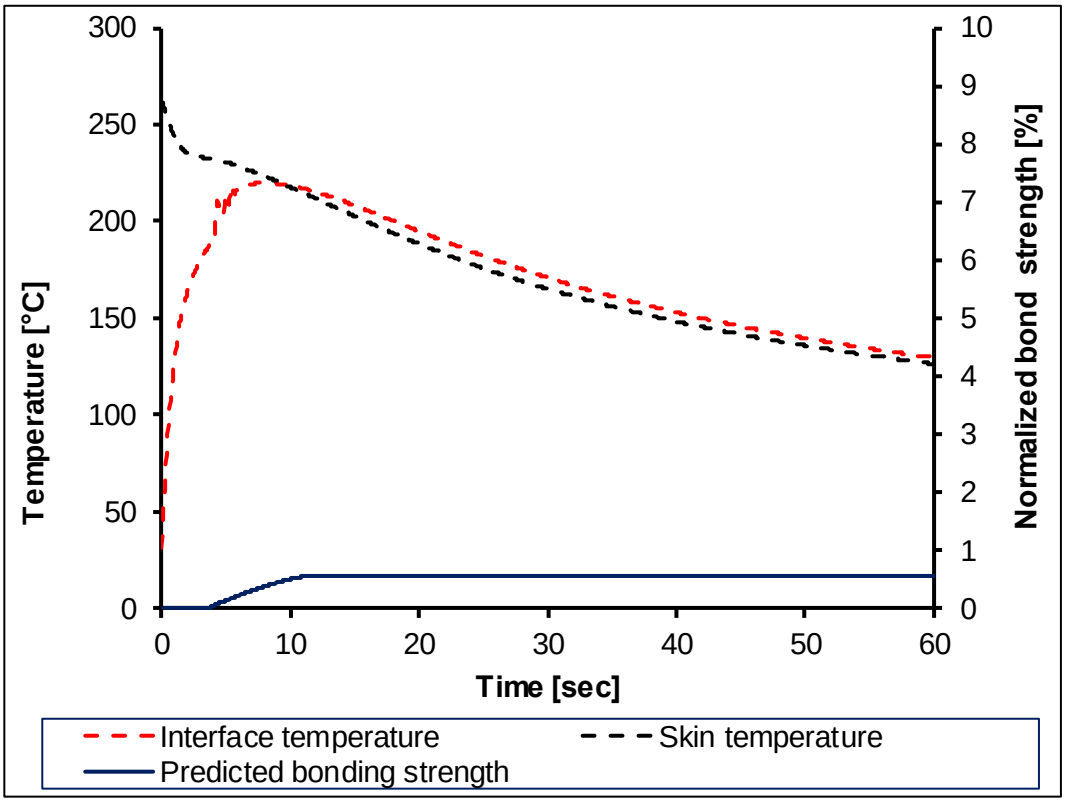


Figure 54: Normalised tensile bond strength prediction for a skin temperature of 260 °C

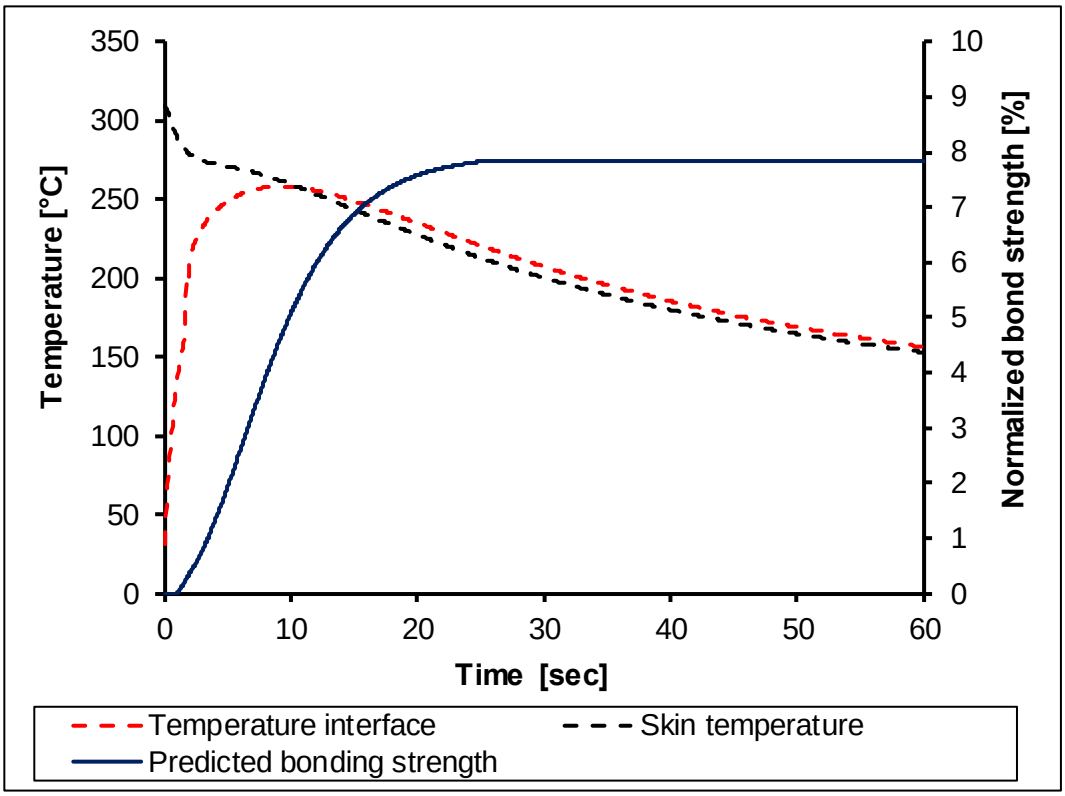


Figure 55: Normalised tensile bond strength prediction for a skin temperature of 310 °C

5.6.3 Bond strength prediction depending on core temperature

The model shows that heating the core leads to an improvement of the bond strength since the temperature level of the core or core surface is already elevated before the heat from the skins is transferred into the core. In combination with heated skins, high temperatures at the interface can be achieved, which improves bond development. Table 19 gives a summary of the predicted normalised bond strengths for several skin temperatures and elevated core temperatures as well as expected failure mechanisms. For a sandwich manufactured with 260 °C heated skins, the sandwich will probably fail adhesively within the interface for core temperatures of 23 °C and 100 °C. By heating the core to 200 °C, the model predicts a normalised tensile bond strength of 5.65 % and failure of the sandwich is expected to be cohesively within the core. In the case of sandwiches manufactured with skins heated to a temperature of 280 °C, a core temperature of 100 °C is probably sufficient to achieve a cohesive failure within the core, since the normalised tensile strength is increased from 2.2 % for a core at room temperature to 7.04 %. An increase of core temperature to 200 °C will lead to a further increase of the predicted tensile bond strength. If the skin is heated up to 300 °C, core heating will improve the predicted bond strength, however it is expected that even sandwiches with the core kept a room temperature feature a sufficient bond quality and will fail within the core. Therefore, heating of the core seems to be unnecessary in this case.

Table 19: Predicted normalised bond strength and failure mechanisms for varying core temperatures and different skin temperatures

T_{Skin} [°C]	260			280			300		
T_{Core} [°C]	23	100	200	23	100	200	23	100	200
Predicted $\bar{\sigma} = \frac{\sigma}{\sigma_\infty}$ [%]	0.56	1.52	5.65	2.2	7.04	12.41	5.05	9.51	25.97
Expected failure mechanism [Adh/Coh]	Adh	Adh	Coh	Adh	Coh	Coh	Coh	Coh	Coh

5.6.4 Discussion

The modelling results are valid provided that the core does not collapse due to the increased temperature during processing. A statement about core collapse cannot be provided by the model. In addition, the model predicts that a skin temperature of more than 370 °C is necessary to achieve full healing ($\bar{\sigma} = 100$ % = 105 MPa). However, since it is sufficient to achieve a tensile bond strength which is superior to the tensile strength of the core itself (weakest link) and the fact that 370 °C leads to skin de-consolidation and core collapse, the aim of achieving full healing is not further pursued.

5.7 MODEL VERIFICATION

This section aims to verify the proposed model with experimental trials in order to determine the process window for successful fusion bonding of CF/PEEK skins and a PEI foam core. Sandwich samples are manufactured according to the parameters as identified by the model, and the skin-to-core bond quality is characterised by mechanical testing. In the following, the experimentally obtained results are compared to the modelling results in order to verify the theoretical approach and discussed in conclusion.

5.7.1 Materials

The skin material consists of eight PEEK pre-impregnated carbon fibre reinforced fabric plies (5HS fabric, 285 g/m² areal weight), symmetrically stacked and consolidated to a thickness of 1.86 mm. The fibre volume fraction is ~52 %. The skins are on one side superficially enriched with Ultem®1000 (Solvay, USA) PEI films with a thickness of 150 µm under a pressure of 0.1 MPa at 400 °C by vacuum moulding as described in chapter 5.3. The final skin thickness is approximately 2 mm. As core structure, the PEI Airex® R82.110 foam with a density of 110 kg/m³ and 20 mm thickness provided by Gaugler and Lutz oHG, Germany is used.

5.7.2 Experimental

5.7.2.1 Specimen preparation

The skins are joined separately one by one to the core during the experimental trials. Sandwich samples with dimensions of 150 mm width and 200 mm length are manufactured, which allows for abstraction of five specimens a 50 mm to 50 mm for testing. To preclude periphery effects, the sandwiches are trimmed 25 mm on each side.

The process is conducted according to the non-isothermal compression moulding setup, which was defined for the modelling approach, see Figure 45 in chapter 5.5.3.1.

The skin is placed on an aluminium transfer plate (15 mm thickness) and heated up in an air-circulating oven (NA 500/45 Nabertherm, Germany) until it reaches the desired skin pre-heat temperature. Thermocouples are integrated into the transfer plate to monitor the transfer plate temperature, which gives an indication about the skin pre-heat temperature. Subsequently, skin and transfer plate are transferred into the press and integrated in a rectangular frame, which is combined with the transfer plate considered the male mould. The transfer takes around 10 - 12 seconds and the heat loss during transfer approximately 20 °C. Pre-trials showed that the use of a transfer plate is necessary to reduce the temperature loss during transfer, see Figure 56.

The skin-to-core joining is performed in a static press (Platenpress P 400 P, Dr. Collin GmbH, Germany). The core is positioned into the female mould which is installed on the upper press platen. Core pre-heating is performed in a second circulating-air oven before installation into the female mould. Once transfer plate and skin are integrated into the rectangular frame (installed on the lower press platen), the mould is closed. To avoid core collapse the pressure is kept low at p = 0.2 MPa (lowest possible pressure for these dimensions at the press) and the process is controlled by the core compaction distance ($d_{compaction}$). Closing of the mould is stopped when female and male mould touch, see chapter 5.4. Since the press surface is heated by heat conduction from the transfer plate, the press is cooled down to room temperature before every manufacturing trial.

Following the modelling results from section 5.6 the skin temperature and the core temperature influence the bond quality significantly. To verify these results, the temperatures for specimen manufacturing are selected in concordance with the parameters applied in the model. In particular, skin temperatures (T_{Skin}) in the range 260 °C – 320 °C are investigated in steps of 10 °C. For the manufacturing process a skin temperature drop of approximately 20 °C during transfer from the oven into the press has to be considered, resulting in oven temperatures of

280 °C – 340 °C. The core temperatures (T_{Core}) are selected according to the modelling approach as room temperature (23 °C) and elevated temperatures of 100 °C, 200 °C. Similar to the definition of the skin temperature, T_{Core} is referred to as the core temperature in the press. A core temperature drop during transfer should be considered as well. A core compaction distance ($d_{Compaction}$) of 2 mm for each side is selected with the result that the core is 4 mm compacted in total, transitioning an initial core thickness of 20 mm to a final core thickness of 16 mm. In combination with the skins having a thickness of approximately 2 mm, a final sandwich thickness (S_{aimed}) of 20 mm is pursued.

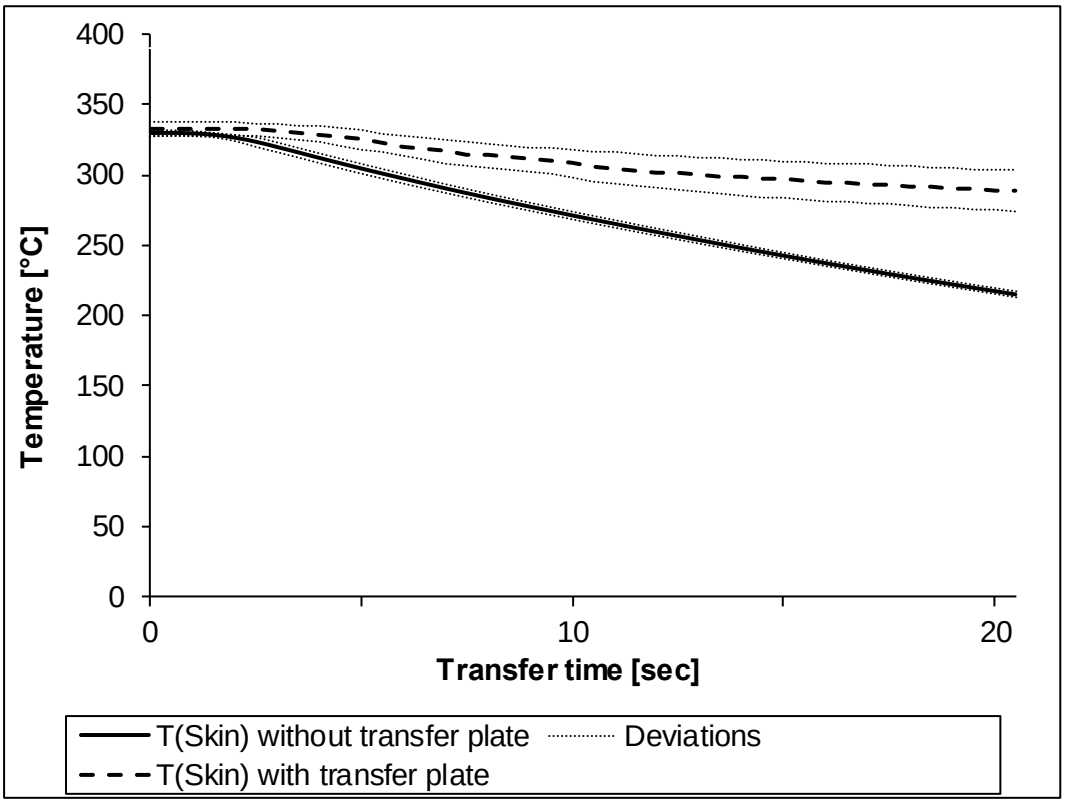


Figure 56: Cooling rate of skins during transfer with and without transfer plate

5.7.2.2 Test setup

Mechanical testing is performed to evaluate the mechanical properties of the skin-to-core interface. The tension test in flatwise plane after DIN 53292 [184] (Figure 57) serves for testing the tensile strength of sandwich specimens. The sandwich specimens (length a and width b are 50 mm) are adhesively bonded to aluminium profiles by means of a thermoset paste adhesive DP490 (3M, USA), which can be integrated in a universal testing machine Instron 5566 (Instron, USA), equipped with a 10 kN load cell. Testing is performed using a constant speed of 0.5 mm/min at room temperature and a relative humidity of 50 %. Five samples for each parameter set are tested. Failure modes of the sandwich specimens are assessed based on the evaluation according to DIN EN ISO 10365 [185], and differentiated between cohesive failure in the centre of the core (Coh), cohesive failure in the boundary layer of the core (B.l. Coh), adhesive failure (Adh) or a mix of adhesive and cohesive failure.

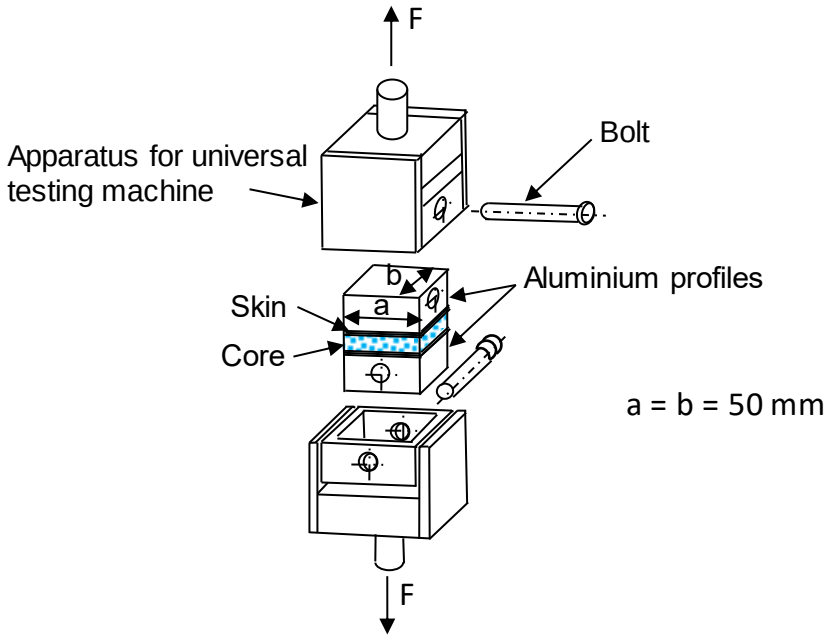


Figure 57: Test setup for the flatwise tension test according DIN 53292 [184]

5.7.3 Bond strength depending on skin temperature

Figure 58 shows the tensile strength results as well as the failure mechanisms of the sandwich specimens manufactured with different skin temperatures. The results are normalised to the tensile strength of bulk PEI (σ_∞) to enable a comparison with the predicted normalised tensile strengths.

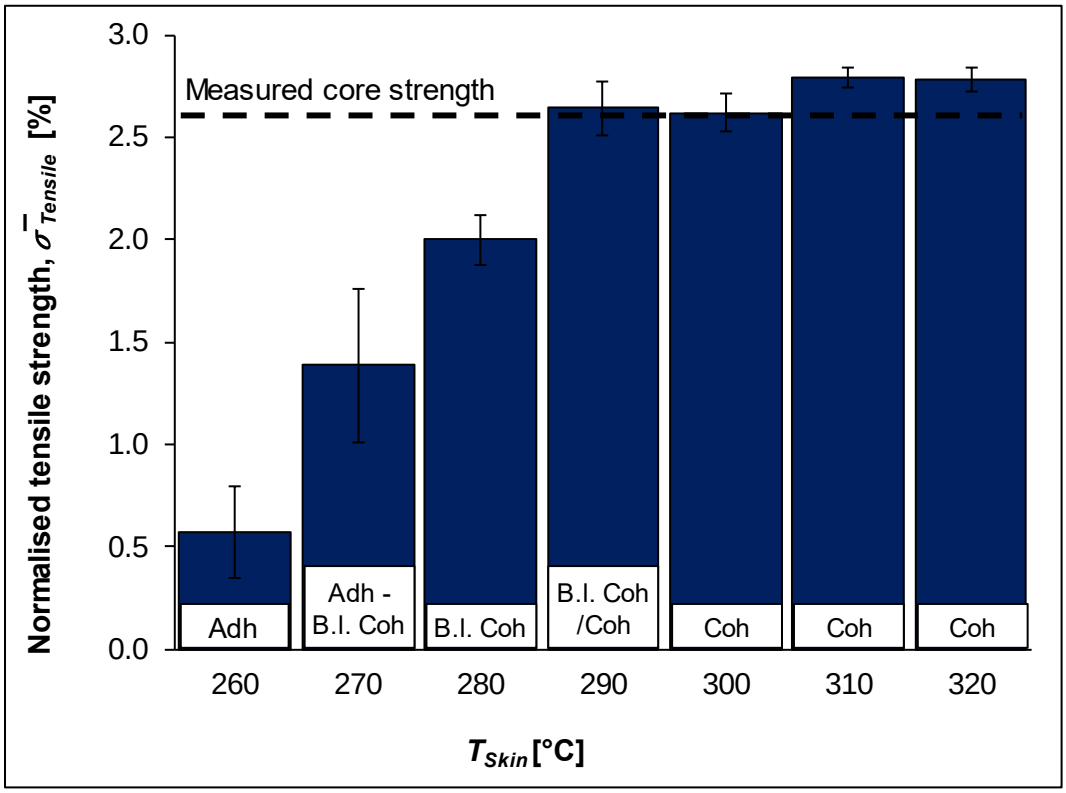


Figure 58: Normalised tensile bond strength results dependent on skin temperatures

The results clearly show the strong influence of skin temperature on bond strength. Samples manufactured at temperatures below 280 °C feature low tensile strengths, while failing adhesively within the interface. For a skin temperature of 280 °C the specimens fail cohesively in the boundary layer of the core. Though the tensile bond strength is about 2 % and below the strength of the core, therefore the failure is designated as adhesive failure. With skin temperatures above 290 °C, the bond strength is significantly increased. However, for T_{Skin} = 290 °C failure in the boundary layer and in the core centre occurred, which is considered an intermediate failure mode. Above skin temperatures of 300 °C all specimens fail cohesively within the core centre, which indicates that the bond is stronger than the core itself. A normalised core tensile was already experimentally verified according to DIN 53292, leading to a normalised tensile strength of 2.64 % (normalised to the PEI bulk tensile strength). Tensile strengths which are higher than the tensile strength of the initial core as characterised for the specimens manufactured with T_{Skin} = 310 °C or 320 °C might be explained by a core densification of the whole core due to heat and pressure which leads to an increase of the core properties. However, a verified conclusion cannot be given since a difference of the failure mechanism in the core centre in comparison to the initial core cannot be detected. In Figure 59 the different failure mechanisms which occur during testing are displayed.

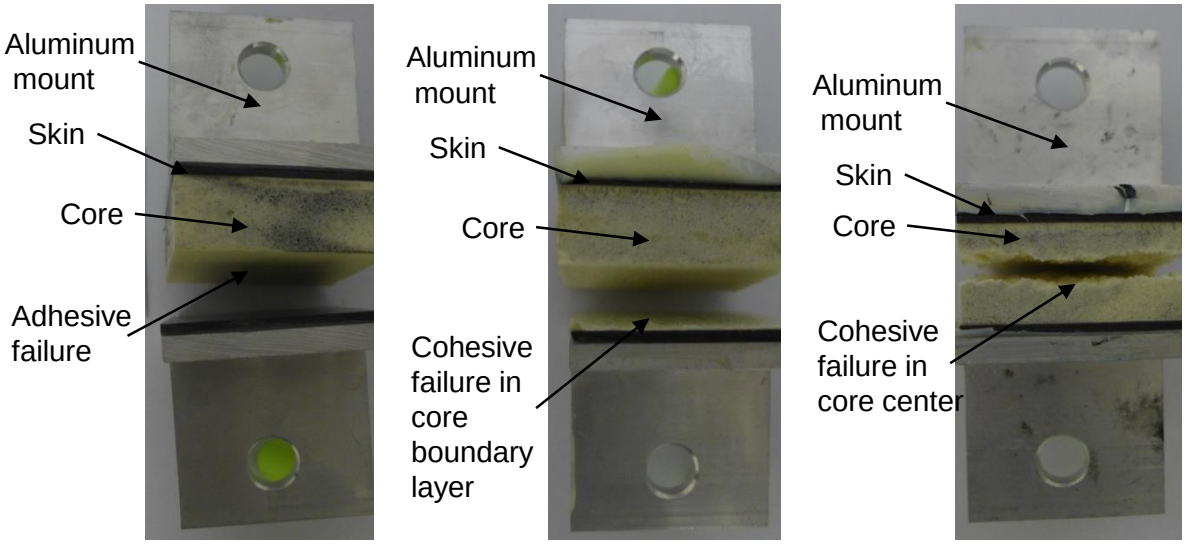


Figure 59: Occurred failure mechanism: a) adhesive failure at T_{Skin} = 260 °C, b) boundary layer cohesive failure at T_{Skin} = 280 °C and c) cohesive failure at T_{Skin} ≥ 300 °C and for the initial foam

5.7.4 Bond strength depending on varying core temperatures

Figure 60 shows the normalised tensile strength results as well as the occurring failure mechanisms of sandwich specimens manufactured with varying core and skin temperatures. As already presented in Figure 58, the joining process of a core kept at room temperature, and heated skins of 260 °C and 280 °C does not lead to a sufficient fusion bond strength due to the lack of heat energy within the interface. Heating of the core leads to partial improvement of the bond quality, since heat energy needed for the fusion bonding process is complemented by the core. By elevating the core temperature to 100 °C, the tensile strengths for specimens manufactured with skin temperatures of 260 °C and 280 °C can be increased from 0.57 % to 1.30 % and from 2.00 % to 2.69 % respectively.

However, for specimens manufactured with a skin temperature of 260 °C, a core temperature of 100 °C is still not high enough to ensure a sufficient fusion bond and the specimens still fail adhesively at the interface. In contrast, joining of a 100 °C heated core and skins at a temperature of 280 °C leads to an increase in the bond quality compared to joining with a core at room temperature with the result that the specimens fail cohesively. Heating the core to 100 °C in combination with 300 °C heated skins does not improve the measured tensile bond strength, but it leads to slight core collapse with the result that evenly distributed contact of the core to skin is not ensured. Therefore, a mix of adhesive and cohesive failure occurs, see Figure 61.

Heating the core to a temperature of 200 °C influences the properties of the sandwich negatively. Specimens manufactured in combination with 260 °C heated skins feature a slightly higher tensile strength compared to specimens manufactured with T_{Core} of 23 °C and 100 °C, though the use of a 200 °C core leads to high variation in bond quality. The specimens fail adhesively as well as cohesively in the boundary layer indicating an uneven distribution of interfacial contact.

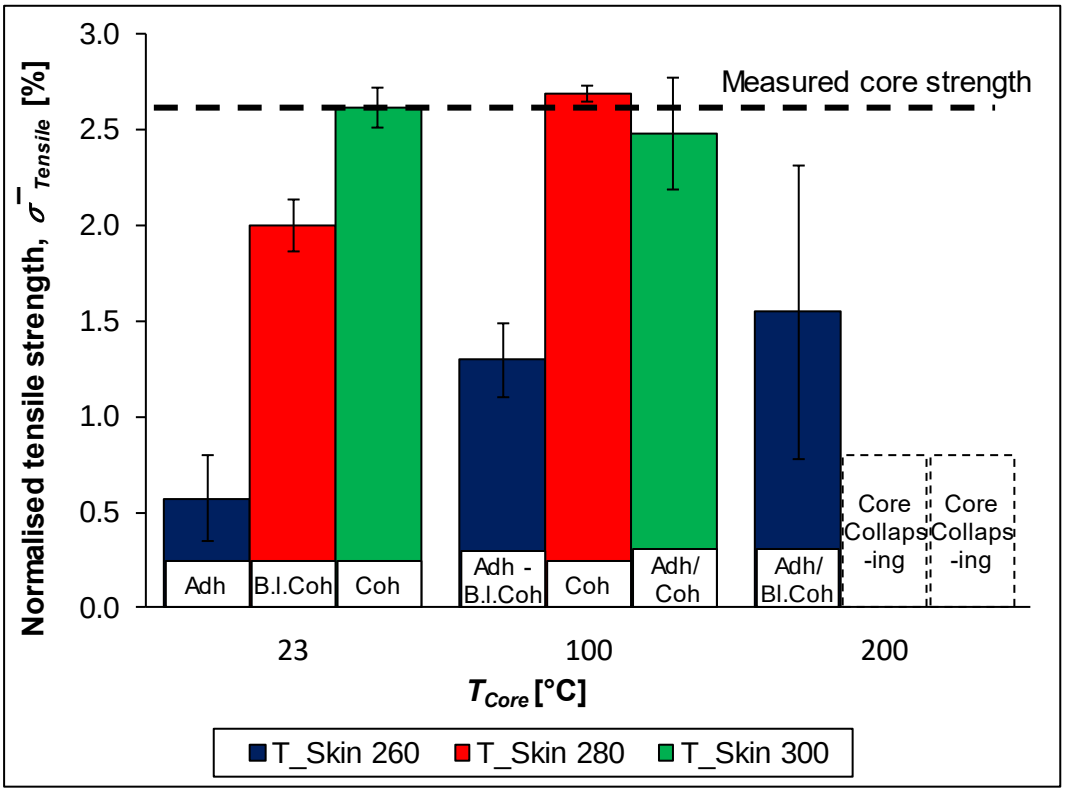


Figure 60: Normalised tensile bond strength dependent on different core temperatures

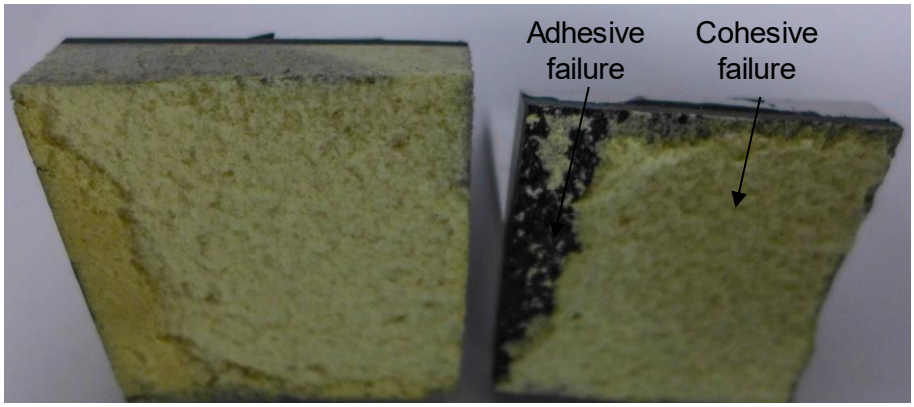


Figure 61: Adhesive and cohesive failure mix at T_{Skin} = 300 °C and T_{Core} = 100 °C

Furthermore, specimens manufactured with skin temperatures of 280 °C and 300 °C in combination with a core heated up to 200 °C cannot be joined at all. Core collapse due to high temperatures is observed. Figure 62 displays the final sandwich thicknesses (S) which help to identify uncontrolled core collapse after processing, since the core compaction is limited by the mould stops. It can be seen that increasing the core temperature leads to a significant decrease of the final sandwich thickness, see Figure 62. In addition, higher skin temperatures lead to lower sandwich thicknesses. By regarding the core structures in Figure 62 an understanding for the different sandwich thickness can be obtained. For example, at a low skin temperature of 260 °C, the core is slightly compacted under load in the boundary layer (Figure 63a), but the desired thickness (S_{aimed}) of 20 mm is not reached as illustrated in Figure 62.

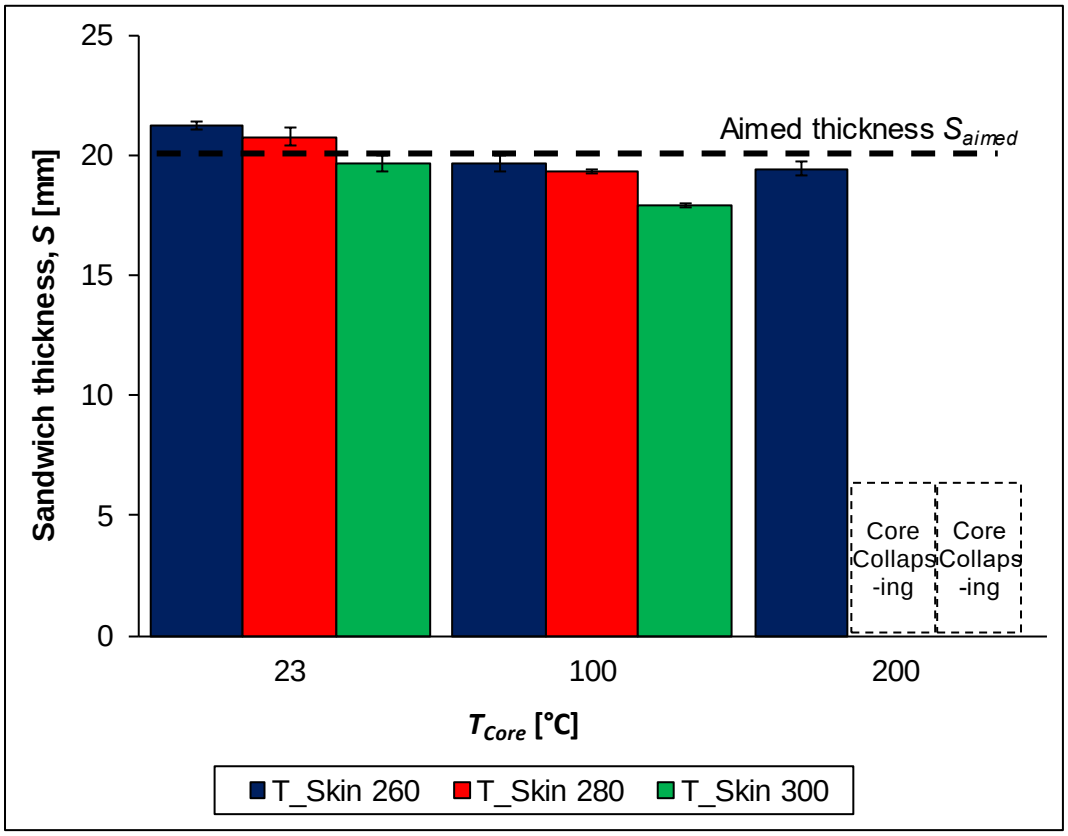
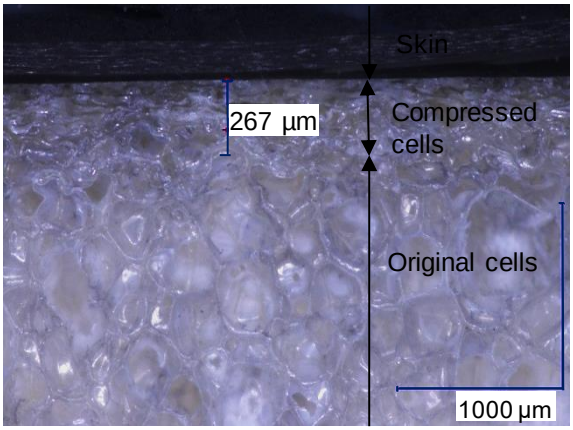
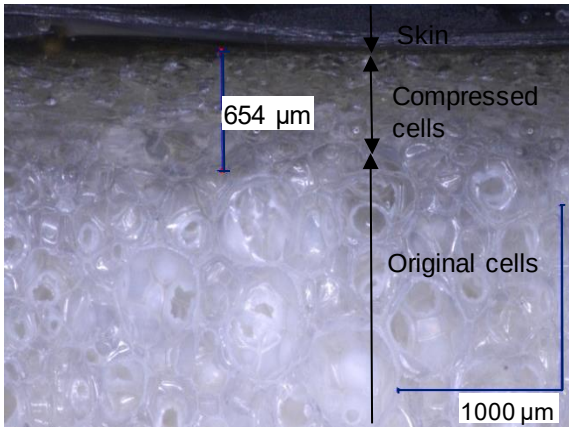


Figure 62: Sandwich thicknesses dependent on varying skin and core temperatures

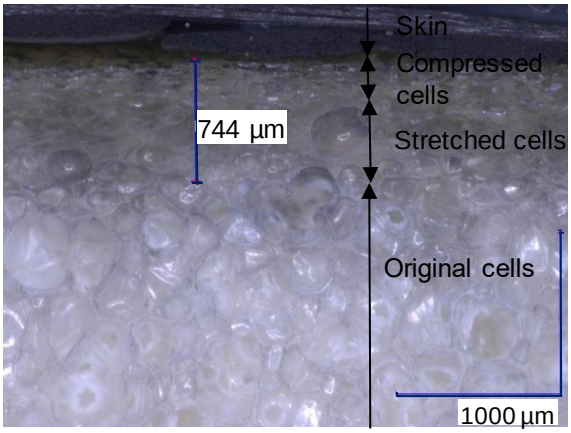
An explanation is the lack of temperature to soften and compact the cells under load. The cells are only compacted within a layer of approximately 267 µm, see Figure 63a. By increasing the skin temperature to 290 °C, the core is compacted more under load and temperature, and the aimed thickness of 20 mm is approximately achieved, see Figure 63b. A layer with compacted cells of approximately 654 µm can be identified. Further increasing the skin temperature to 300 °C, leads to a final sandwich thickness of 19.66 mm, which is below the aimed thickness, see Figure 62. In the case that the core is heated up to 100 °C and combined with 300 °C heated skins the final thickness is even further reduced (S = 17.94 mm). Figure 63c and Figure 63d show the core structure of specimens manufactured with skins heated to 300 °C and a core at room temperature (c) and a core at 100 °C (d). It can be observed that the cells, which are close to the skin, are compressed, but further towards the centre of the core the cells are stretched and feature an open structure. Remarkably, the potting resin flows into the core structures in the boundary layer and not into the cells below, although the core usually features a closed cell structure, which hinders substances from flowing into the cells. It indicates that the cells in the boundary layer are damaged, specifically the cell walls, leading to an open cell structure of the core in the boundary layer. This shows that during processing at high temperatures, the core towards the centre collapses and stretches the boundary layer cells, since the skin and bonded core surface cannot follow the movement due to the mould stops. However, a significant change of the cell structure in the core centre cannot be identified, since the initial core already features an unevenly distributed cell size structure.



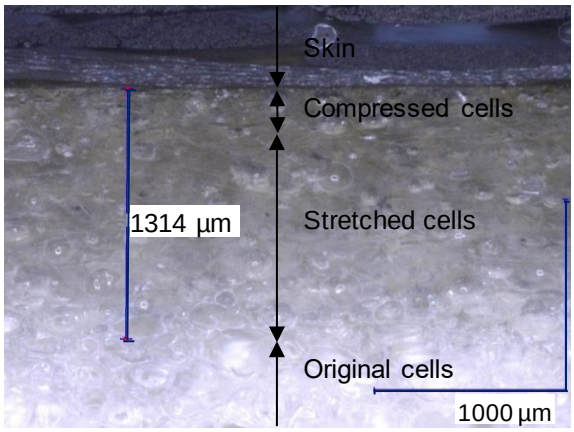
a) T_{Skin} = 260 °C / T_{Core} = 23 °C



b) T_{Skin} = 290 °C / T_{Core} = 23 °C



c) T_{Skin} = 300 °C / T_{Core} = 23 °C



d) T_{Skin} = 300 °C / T_{Core} = 100 °C

Figure 63: Core structure after processing with a) T_{Skin} = 260 °C and T_{Core} = 23 °C, b) T_{Skin} = 290 °C and T_{Core} = 23 °C, c) T_{Skin} = 300 °C and T_{Core} = 23 °C, d) T_{Skin} = 300 °C and T_{Core} = 100 °C

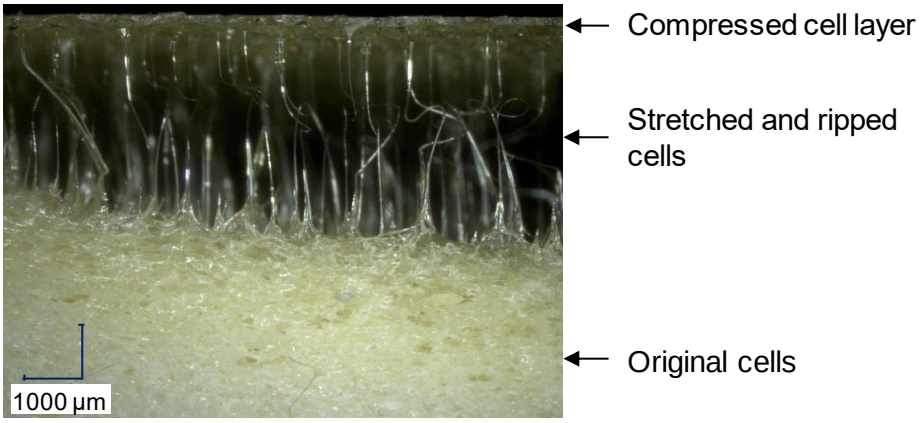


Figure 64: Stretched and ripped cells caused by core collapse and a compacted cell surface layer at T_{Skin} = 300 °C and T_{Core} = 200 °C

In the case of the core being heated to 200 °C and combined with heated skins of 280 °C or 300 °C, the core collapses to a greater extent and the cells are ripped when stretched, see Figure 64. As a result, sandwich manufacturing under these circumstances is not possible.

5.7.5 Comparison to predicted results

5.7.5.1 Bond strength depending on varying skin temperatures

Figure 65 displays the comparison of the predicted and measured normalised tensile strengths together with their failure mechanisms depending on the skin temperatures in combination with a core kept at room temperature. A good agreement between predicted and measured strengths and failure modes for skin temperatures of 260 °C – 280 °C is achieved. According to the model, the tensile bond strengths of sandwich samples manufactured with a skin temperature in the range 290 °C up to 320 °C and a core kept at room temperature should have increased normalised bond strengths from 3.35 % up to 13.13 %. Since the predicted strengths are above 2.64 % (normalised core strength), the model predicts cohesive failure. In agreement, all experimental sandwiches manufactured with skin temperatures above 290 °C fail cohesively within the core, featuring normalised tensile strengths of around 2.7 %. The difference between the predicted and measured normalised tensile strengths can be explained by the limiting strength of the core, which presents the weakest link and is not taken into account in the model. The model is only able to predict the tensile bond strength but not to predict the tensile strength of the sandwich as a whole.

5.7.5.2 Bond strength depending on varying core temperatures

A comparison between predicted and tested tensile strength (normalised) is given in Figure 66. According to the model, a skin heated to 260 °C in combination with a core kept at room temperature or heated up to 100 °C cannot be fusion bonded properly to the core, which is confirmed by experimental trials showing adhesive failure within the interface. In the case of a skin temperature of 280 °C and an increase of core temperature to 100 °C the model predicts a significant improvement in the bonding quality. The predicted cohesive failure is confirmed by experimental trials. An increase of the core temperature to 100 °C in combination with heated skins of 300 °C leads to an improvement of the bond quality in comparison to the use of a core kept at room temperature according to the model. This is not confirmed by experimental trials, because heating the core leads to core collapse, resulting in a decrease of the bond strength. According to the model, a further heating of the core up to 200 °C leads to higher tensile bond strengths resulting in cohesive failure for all three skin temperatures. However, the experimental trials show a negative influence of a core temperature of 200 °C since the foam tends to collapse at high temperatures. Core collapse is not considered in the modelling approach, therefore, the predictions differ at higher core temperatures from the experimentally obtained results and have to be treated with caution.

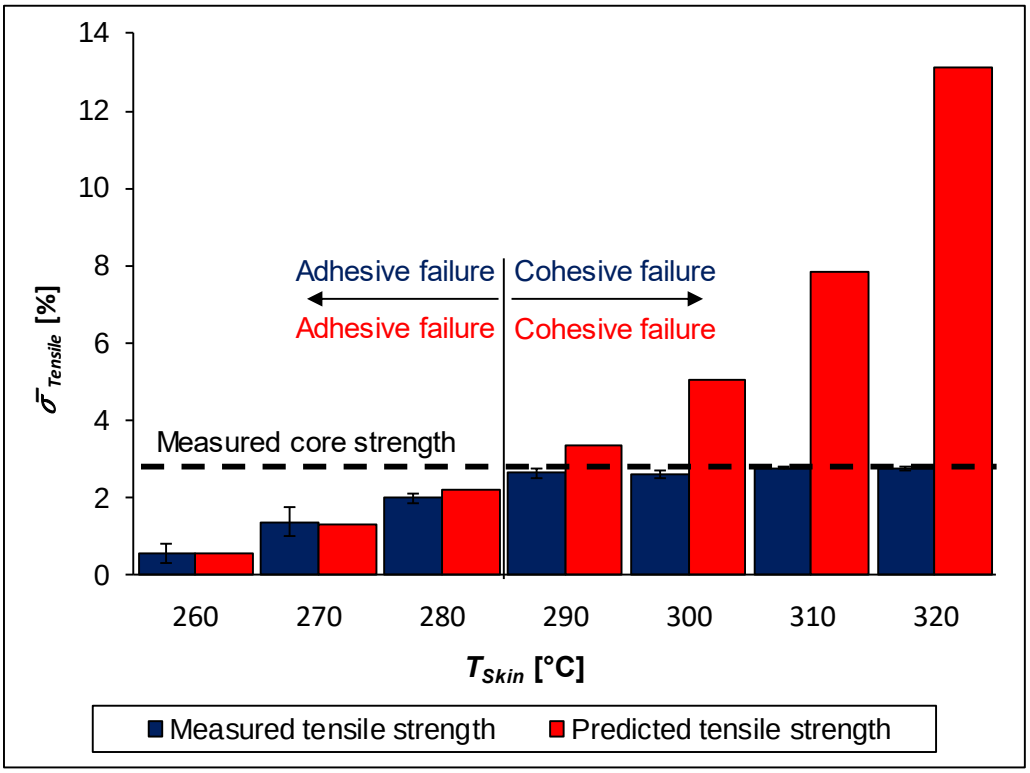


Figure 65: Comparison of measured and predicted bond strength dependent on different skin temperatures

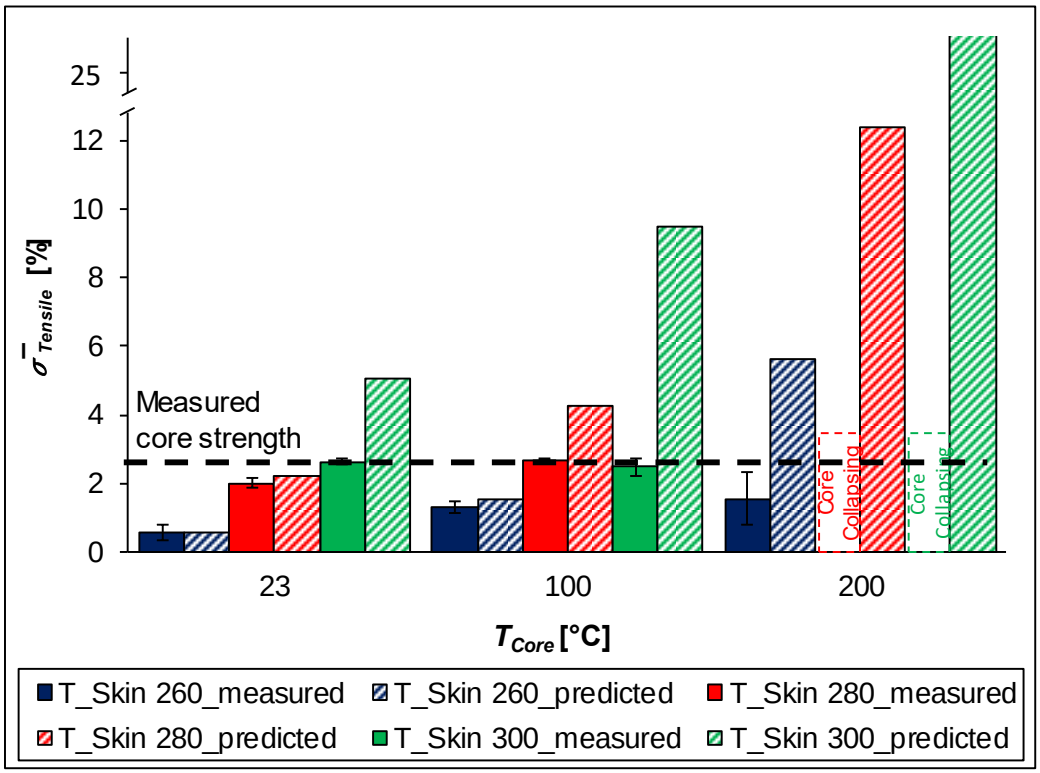


Figure 66: Comparison of the measured and predicted bonding strength dependent on varying core temperatures and different skin temperatures

5.8 DISCUSSION

The experimental trials show that the modelling approach can successfully predict the tensile failure modes of the sandwiches that occur during testing. Since the model predicts the normalised tensile bond strength of the interface and not the tensile strength of the sandwich as whole, differences between the predicted tensile bond strength and the measured tensile strengths occur. In the cases where the interface tensile bond strength is below the tensile core strength the model allows an accurate prediction of the bond strength and the mode of failure. In the cases where the bond strength is above the core strength, the model is only able to predict the mode of failure based on the weakest link, which in these cases is the core and not the interface. Furthermore, experimental trials show that extensive heating of the core (200 °C) leads to core collapse, which is not considered in the model. In order to avoid incorrect model prediction due to the missing evaluation of core collapse, it seems useful to take a detailed look at the heat flow from the skins into the core during processing (Figure 67) followed by an analysis of the thermal stability of the foam. For example, by heating the skins up to 300 °C and keeping the core at room temperature, the core surface is heated up far above 217 °C (T_g of PEI), whereas the core centre (2 mm – 5 mm) stays below 217 °C, see Figure 67a. The core centre is not softened and core collapse can be avoided. In comparison, if the core is heated to 200 °C and combined with 300 °C heated skins, the core surface as well as the core centre is heated far above 217 °C (Figure 67b). This means that the whole core structure is softened and core collapse can occur.

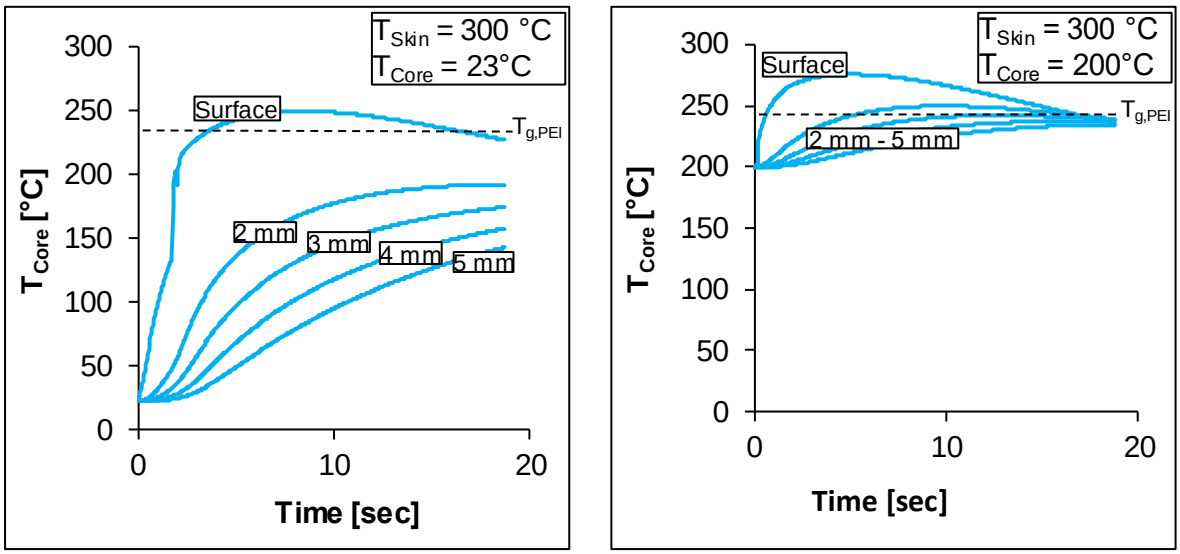


Figure 67: Calculated heat flow into the core for a) T_{Skin} = 300 °C and T_{Core} = 23 °C b) T_{Skin} = 300 °C and T_{Core} = 200 °C

For the determination of a suitable process window, the following procedure is proposed.

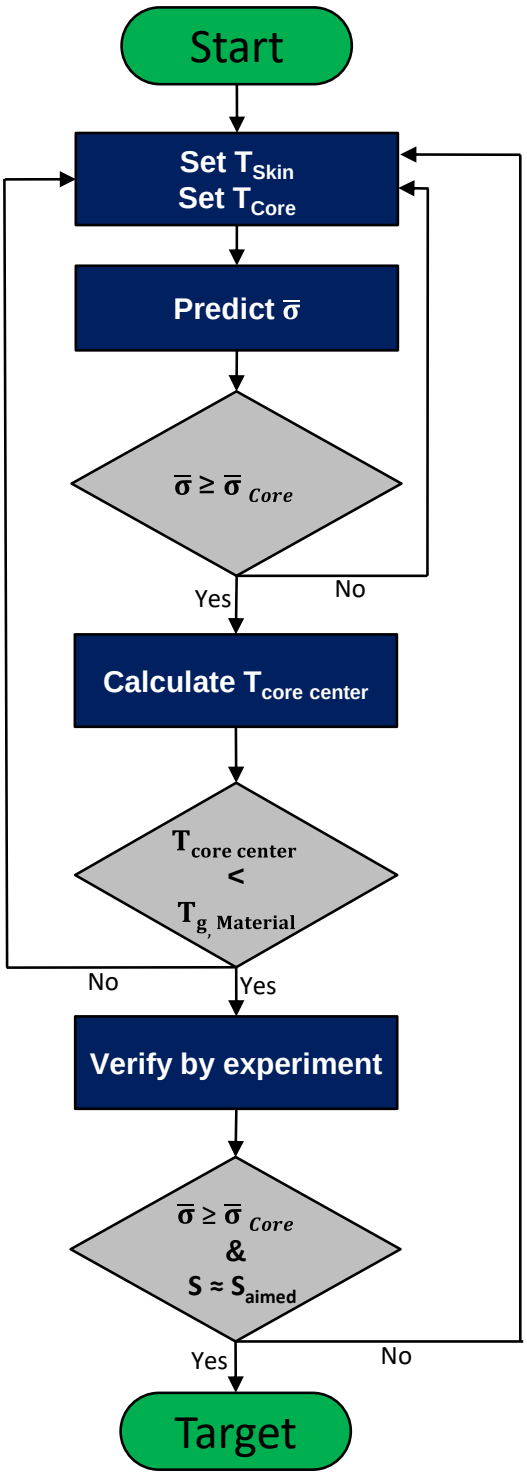


Figure 68: Flow chart for process window determination

6. MECHANICAL CHARACTERISATION

In the previous chapter, the process window for fusion bonding carbon fibre reinforced Polyetheretherketone (CF/PEEK) skins, superficially enriched with a Polyetherimide (PEI) layer, and a PEI foam is determined based on a modelling approach and verified by tensile testing. In particular, the influences of the skin temperature T_{Skin} and the core temperature T_{Core} on the skin-to-core bond quality are investigated. According to the theory, T_{Skin} and T_{Core} predominantly influence the fusion bond strength. The investigations show that skin temperatures in the range of 290 °C – 320 °C in combination with a core kept at room temperature are required to enable a fusion bond between skins and core, which is stronger than the core strength itself. Furthermore, the investigations show that heating the core can slightly improve the bond quality, albeit it leads in most cases to core collapse.

However, tensile testing results give only a first indication about the sandwich performance, in particular the bond strength, since the results are only based on a tensile load case. However, during service sandwiches are mostly exposed to compression or bending loads. In order to be able to assess the CF/PEEK – PEI sandwiches for possible use cases, further mechanical properties need to be characterised, see requirements in chapter 1.2. In addition, as highlighted in chapter 5.4 further parameters besides T_{Skin} and T_{Core}, in particular the core compaction distance and the PEI film thickness, might also influence the sandwich quality. Therefore, these possible influences need to be understood as well.

To achieve these goals, the influences of varying skin temperatures *(T_{Skin})*, different core compaction distances *($d_{compaction}$)* as well as varying PEI film thicknesses *(h_{PEI})* on the tensile, drum-peel, compression, shear, flexural and impact properties are determined and presented in this chapter. The core temperature *(T_{Core})* is not further investigated due the increased risk of core collapse.

Furthermore, as stated in the goals of this thesis (chapter 3), an additional aim is to compare the developed thermoplastic sandwiches with state-of-the-art thermoset sandwiches at a later time point (chapter 7). In order to realise sandwich structures on a comparable basis, the material configurations used in skins and core in the previous investigations need to be changed and adapted to material configuration available for thermoset sandwiches. Materials applied in the previous chapter were simply selected according to requirements and availability. By adapting the configuration of the TPC sandwich to a comparable level the core density is lowered from 110 kg/m³ to 60 kg/m³, and the core thickness is additional reduced from 20 mm to 15 mm. Furthermore, the skins configuration is changed to three ply setup having lower fibre areal weights.

By doing so, it is accepted that the process window determined by modelling (chapter 5) cannot be transferred par for par to the new material configuration. However, the determination of the model input parameter for the new materials goes beyond the scope of this thesis. To ensure the ability to produce sandwiches with the new models according to the determined process window, pre-trials were conducted which showed the successful production with the changed material setup.

6.1 MATERIALS

The sandwich skins consist of two carbon fibre reinforced PEEK fabric plies arranged in (±45°) and (0°,90°) orientation combined with two carbon fibre reinforced unidirectional (UD) PEEK layers (+45°/-45°). The two UD layers are aimed to substitute one (±45°) fabric ply to ensure a quasi-symmetrical setup. The hybrid skin set-up consisting of fabrics and unidirectional layers is selected due to the fact that the UD layers avoid extensive diffusion of the PEI polymer into the laminate during consolidation, see chapter 5.3. The fibre volume fraction of the consolidated laminate is approximately 60 %. The skins are on one side superficially enriched with Ultem®1000 (Solvay, USA) PEI films with varying thicknesses *(h_{PEI})* of 125 µm and 175 µm during consolidation at 375 °C and 1 MPa. For the core structure, PEI Airex® R82.60 foams with a density of 60 kg/m³ and varying thicknesses of 17 mm, 19 mm and 21 mm provided by Gaugler and Lutz oHG, Germany are used.

6.2 EXPERIMENTAL

6.2.1 Specimens preparation

In this study the influence of the skin temperature (T_{Skin}), the influence of the core compaction distance ($d_{compaction}$), and the influence of the PEI enrichment thickness of the skins (h_{PEI}), on the sandwich properties will be investigated. The core compaction distance is thereby defined as the difference between the initial core height realised by different initial core thicknesses, and the aimed or final core height after compaction, see more detail in chapter 5.4. The core is kept at room temperature for all investigations. The process parameters are listed in detail in the test matrix in Table 20 and specimens are designated according to the following order of process parameters: $\boldsymbol{T_{Skin}}$ **-** $\boldsymbol{h_{PEI}}$ **-** $\boldsymbol{d_{compaction}}$. As a reference for all series a skin temperature of 300 °C, a core compaction distance of 2 mm and a PEI film thickness of 125 µm is selected (specimens 300 - 125 - 2) and all results are compared and normalised to this parameter setup. A final total sandwich thickness *(S_{aimed})* of 16.3 mm is aimed for all samples.

Table 20: Test matrix for complementary characterisation

Specimen-designation	**300-125-2**	310-125-2	320-125-2	300-125-1	300-125-3	300-175-2
T_{Skin} [°C]	**300**	**310**	**320**	300	300	300
T_{Core} [°C]	**23**	23	23	23	23	23
$d_{compaction}$ [mm]	**2**	2	2	**1**	**3**	2
p [MPa]	**0.2**	0.2	0.2	0.2	0.2	0.2
h_{PEI} [µm]	**125**	125	125	125	125	**175**

Thermoplastic composite (TPC) sandwich panels with a dimension of 450 mm by 550 mm are manufactured according to the process presented in chapter 5, see Figure 45. This allows the extraction of the specimens needed for different types of testing as well as trimming of the sandwiches at each side to preclude periphery effects.

6.2.2 Test setup

The tension test in flatwise plane is performed according to DIN 53292 [184]. The sandwich specimens are adhesively bonded by means of a room temperature curing thermoset adhesive DP490 (3M, USA) to aluminium profiles, which can be integrated in a universal testing machine Instron 5566 (Instron, USA), equipped with a 10 kN load cell. Testing is performed using a constant speed of 0.5 mm/min at room temperature and a r.H. of 50 %. The specimens have dimensions of 50 mm by 50 mm.

Climbing drum-peel testing is performed according to DIN EN 2243-2 [186]. The dimensions of the specimens are 75 mm by 175 mm, though only 125 mm length is considered for the determination of the peel force. The peel force is calculated by subtraction of the bending force of the skin from the total measured force. Since a considerable amount of skin flexibility is required for this test, the outer ±45° fabric ply is left out. Specimens are tested using a universal testing machine Zwick 1474 (Zwick GmbH & Co. KG), which is equipped with a 100 kN load cell. The testing speed is constant at 5 mm/min.

Shear tests are performed in accordance with DIN 53294 [187]. The specimens are 250 mm long and 50 mm wide and adhesively bonded to steel loading plates by means of a film adhesive AF163-2 Scotch-Weld™ (3M, USA), which is cured under load (0.1 MPa) in a press at 120 °C. The specimens are tested using a universal testing machine Zwick 1474 (Zwick GmbH & Co. KG), which is equipped with a 100 kN load cell. The testing speed is again constant at 5 mm/min. For these three test standards failure modes of the sandwich specimens are evaluated based on DIN EN ISO 10365 [185], and differentiated between cohesive failure in the centre of the core (Coh), cohesive failure in the boundary layer of the core (B.l. Coh), adhesive failure (Adh) and a mix of adhesive and cohesive failure (Adh + Coh).

According to DIN EN 6061 [188] the four-point bending test is performed in order to determine the flexural properties of flat sandwich constructions. The test specimens are 500 mm long by 80 mm wide, supported on 30 mm diameter steel bars at a span of 460 mm and loaded at quarter points (300 mm span) also by 30 mm steel bars. Wooden inserts are glued by means of a room temperature curing thermoset adhesive paste DP490 (3M, USA) at both ends of the sandwich to prevent compression failure at the load bars. Testing is performed at a constant speed of 12 mm/min using a universal testing machine Zwick 1474 (Zwick GmbH & Co. KG) equipped with a 100 kN load cell.

The edgewise compressive strength test method is conducted according to the test standard ASTM C364 [189]. Specimens with the dimension of 105 mm by 50 mm are tested. To improve the force introduction during testing aluminium blocks are integrated by means of a room temperature curing thermoset adhesive DP490 (3M, USA) at both ends. A universal testing machine Zwick 1474 (Zwick GmbH & Co. KG) is equipped with a 100 kN load cell. Testing is performed using a constant speed of 0.2 mm/min. According to the standard failure, modes are differentiated between skin separation or skin buckling, skin compression failure and core compression or shear failure.

The compression test in flatwise plane is performed according to DIN 53291 [190]. The sandwich specimens have dimensions of 50 mm by 50 mm. Testing is performed using a universal testing machine Instron 5566 (Instron, USA), equipped with a 10 kN load cell. The testing speed is constant at 1 mm/min.

Compression after impact (CAI) testing seeks the determination of residual compression strength after impact loading. The test is performed according to AITM 1-0010 [191]. The specimens have a length of 150 mm and a width of 100 mm and are equipped with aluminium blocks at both ends to ensure improved load introduction during compression testing. The specimens are impacted with 3 J and 5 J by a falling weight conducted by a dart-drop testing device (Myrenne GmbH, Germany). After impacting, the damaged area is analysed according to AITM 1-0010 for damage depth and area. Following, the residual compression strength is characterised using a universal testing machine Zwick 1474 (Zwick GmbH & Co. KG) equipped with a 100 kN load cell. Testing is performed using a constant speed of 0.5 mm/min. For all the presented testing standards, a minimum of five specimens are tested and an average value as well as the deviations are calculated.

The thickness of the sandwich specimens is measured by means of callipers at five locations of each individual specimen and averaged for each process parameter series. Furthermore, all specimens are weighed using a scale (UW6200H, Shimadzu UK Ltd, UK) after drying for 24 hours at 80 °C in an oven (Nabertherm NA 500/45, Germany) and the averaged areal density (g/m²) is calculated for each combination set of process parameters.

6.3 RESULTS

In the following section, an overview of the results concerning each investigated parameter is presented in order to reduce the extent of result. More detailed results as well as standard deviations are presented in Appendix B.

6.3.1 Influence of skin temperature (T_{Skin})

The investigations on the influence of the skin temperature show that the selected skin temperatures of 300 °C, 310 °C and 320 °C enable the successful production of sandwich with a strong fusion bond between skins and core. Figure 69 summarises the mechanical properties of the TPC sandwiches manufactured with different skin temperatures. All results are normalised to the performance of the reference sandwich specimens 300-125-2. The results show that heating the skins to higher temperatures (T_{Skin} = 310 °C, 320 °C) in comparison to the reference skin temperature of 300 °C significantly improves the tensile and the peel strength, while properties such as compression, bending or edgewise compression are marginally influenced by a variation of the skin temperature. To highlight the influence on tensile strength, Figure 70 shows the normalised tensile strength results depending on varying skin temperatures in more detail, including failure mechanisms and sandwich thicknesses. The results show that all three skin temperatures ensure a bond strength that is higher than the core strength itself, leading to cohesive failure of the core in the area adjacent to the skins, which is referred to as the boundary layer, see for example Figure 71. However, on a closer examination, different thicknesses of the boundary layer can be observed. For specimens manufactured with 300 °C heated skins, failure occurs ~400 µm into the core, see Figure 71a. In comparison, Figure 71b shows that for specimens manufactured with a skin temperature of 320 °C, failure occurs approximately 950 µm away from the core surface. Furthermore, differences in the tensile strength can be noticed. The tensile strength of sandwich specimens manufactured with T_{Skin} = 300 °C is significantly below the normalised tensile strength of the initial foam ($\bar{\sigma}_{Core}$ = 1.24), which was characterised as well, while the tensile strength of the

specimens manufactured with 310 °C and 320 °C is almost equal to this value. This indicates that the core structure and its performance are influenced by joining process.

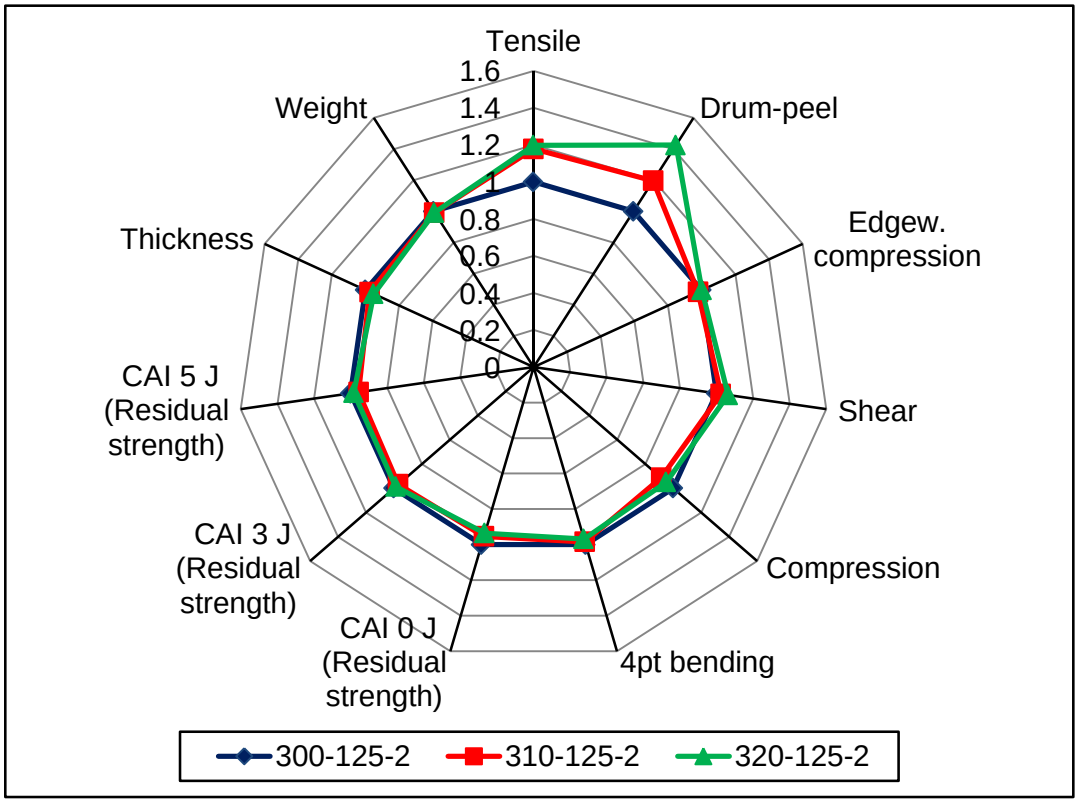


Figure 69: Influence of the skin temperature on the mechanical properties

In the previous chapter (chapter 5.7), it was already observed that the process temperatures influence the sandwich thickness and thereby the core cell structure. Skin temperatures of 300 °C in combination with a core kept at room temperature led to core cell compaction in the boundary layer, while skin temperatures of 300 °C in combination with a heated core of 100 °C led to stretched cells in the boundary layer. Stretching of the cells is assumed to result from inner core collapse towards the centre. During processing the core collapses due to extensive heating, though skin and core surface, which is strongly bonded to the skins, cannot follow the core collapsing movement towards the centre due to the limited mobility of the skins regulated by mould stops. The relative movement of core centre and core surface area leads to stretching of the cells in the boundary layer. Collapse of the core hindered the fusion bonding process due to the missing interfacial contact. However, it could not be observed that the change of the core influenced the core performance itself. A similar phenomenon can be observed in this complementary study, though in contrast to the previous results the performance of the core is thereby influenced. Therefore, this phenomenon is described in detail in the following section.

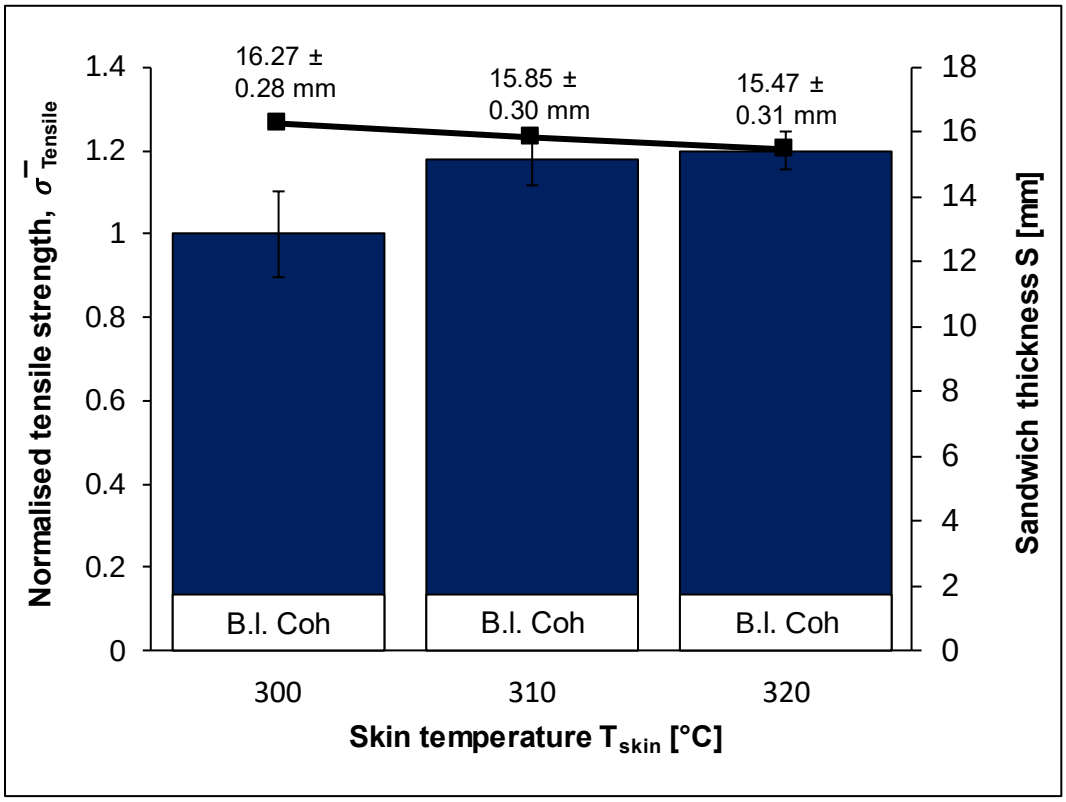


Figure 70: Influence of the skin temperature on the tensile strength (bars) and sandwich thickness (line)

Figure 70 illustrates the decrease of sandwich thickness with the increase of skin temperature. For skin temperatures of 300 °C, the specimens reach approximately the aimed thickness of 16.3 mm. For skin temperatures of 310 °C and 320 °C the sandwich thicknesses are significantly below S_{aimed} = 16.3 mm. Since the mould design hinders extensive compaction of the core under load, sandwich thicknesses below 16.3 mm indicate core collapse during processing. Figure 72 shows micrographs of the cell structure of the core close to the skins of specimens manufactured with skin temperatures of 300 °C (a) and 320 °C (b), one untreated (upper picture) and one potted in epoxy resin and sanded (lower picture). The affected cells in the boundary layer are clearly visible in the upper pictures of Figure 72. A visual comparison between the cell structures in the core centre or beyond the boundary layer and original core cell structures does not reveal a noticeable effect on the cells. As observed in the investigated specimens in chapter 5.7, the potting resin flows again into the affected cells in the boundary layer, see lower pictures of Figure 72.

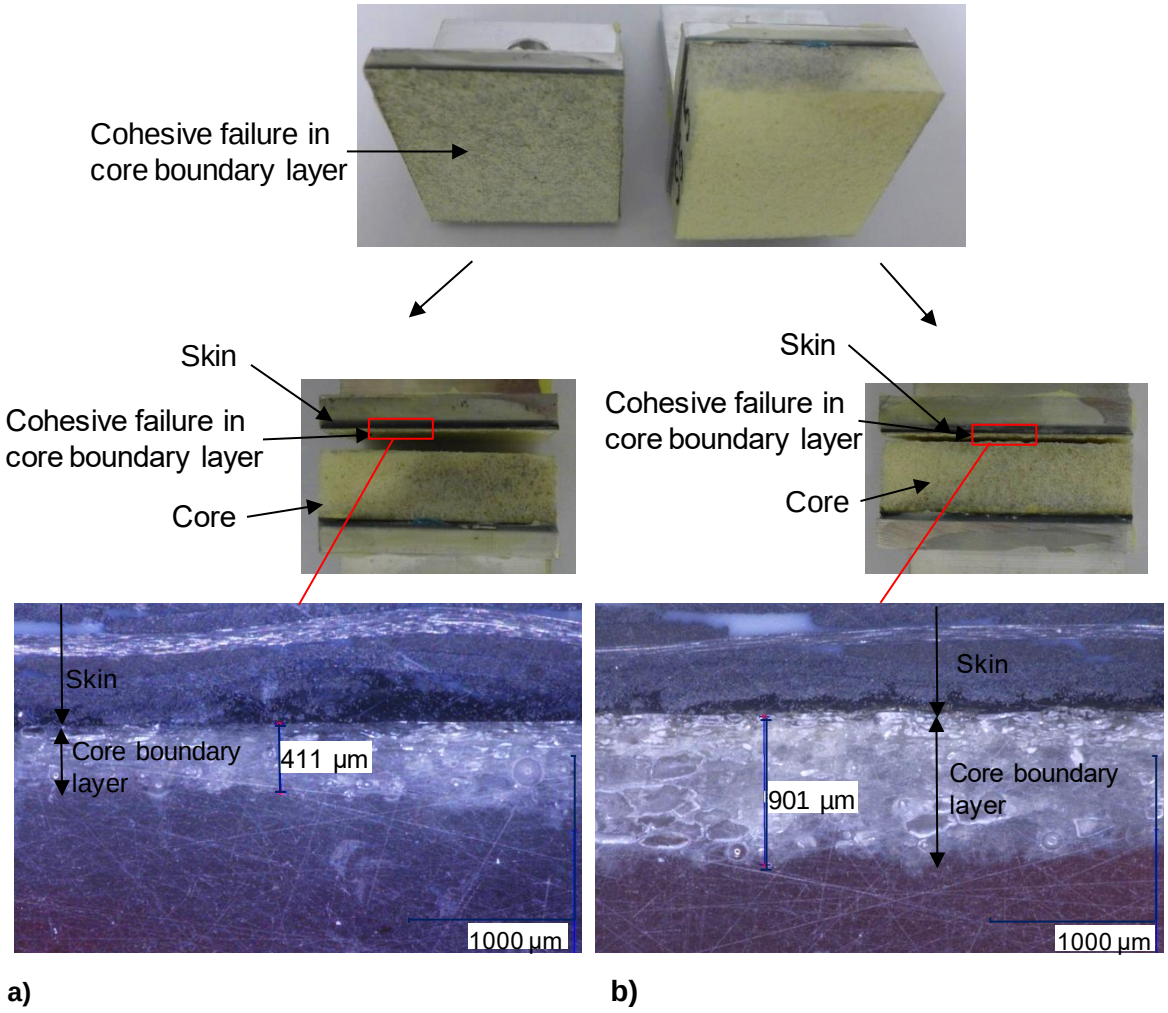
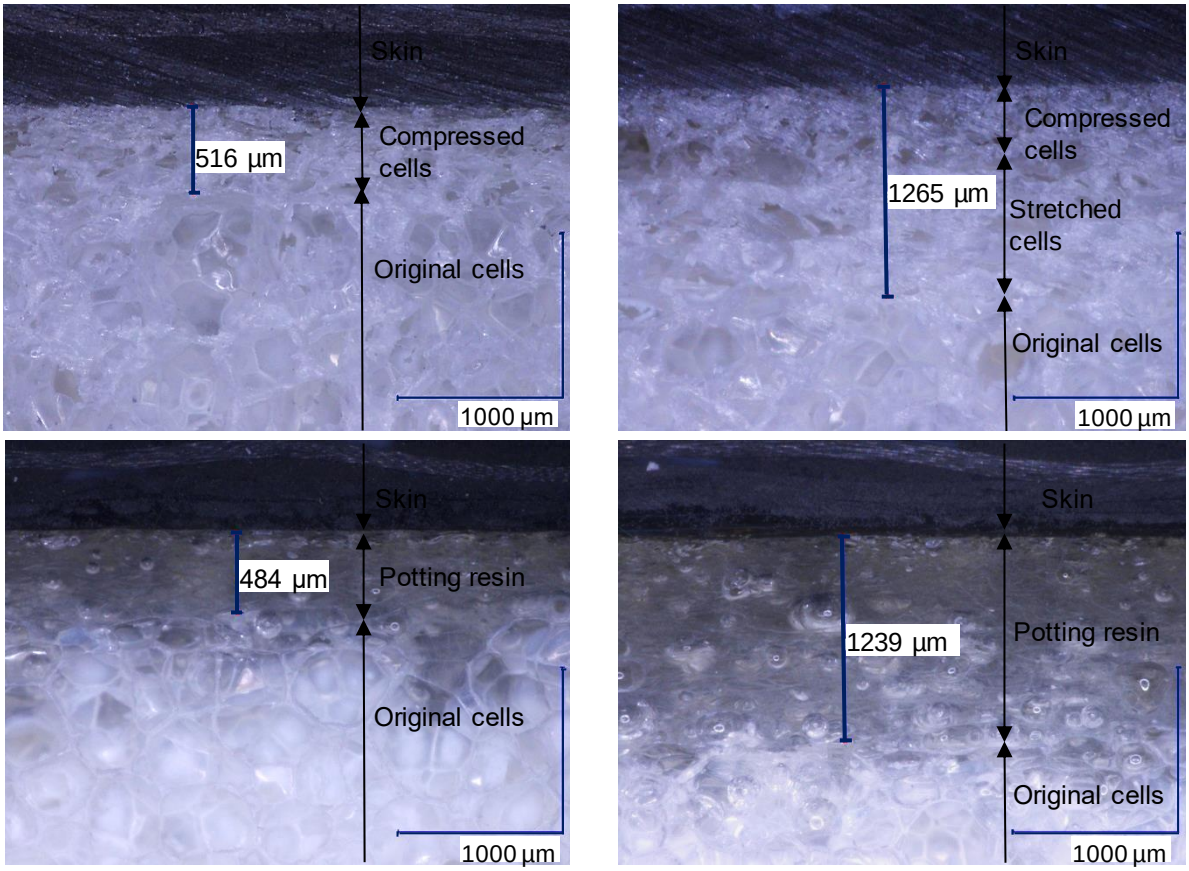


Figure 71: Thickness of the boundary layer of a) specimens 300-125-2 and b) specimens 320-125-2

By comparing the affected cell structures in the boundary layer of the specimens 300-125-2 and 320-125-2 various effects of the temperature on the cells can be detected. Specimens manufactured with skin temperatures of 300 °C feature compacted cells in the boundary layer (Figure 72a), while those with skin temperatures of 320 °C show compacted and stretched cells in a larger boundary layer, see Figure 72b.



a) T_{Skin} = 300 °C b) T_{Skin} = 320 °C

Figure 72: Cell structure in the boundary of a) specimens 300-125-2 and b) specimens 320-125-2 (without potting resin in the upper picture and potting resin in the lower picture)

For better illustration, Figure 73 highlights the stretched in the boundary layer of the specimens 320-125-2.

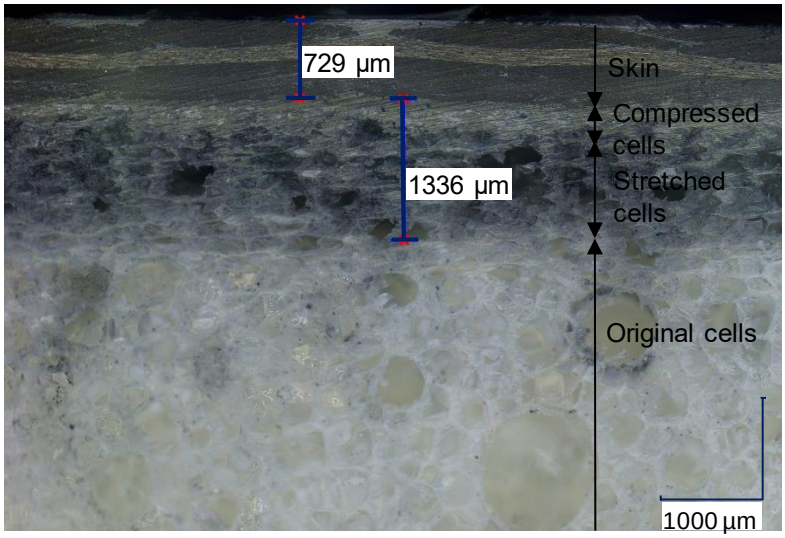


Figure 73: Highlighted boundary layer with stretched cells (without potting resin)

By comparing the cell structures presented in Figure 72 to the location where the failure in the boundary layer occurred (Figure 71) it can be observed that the specimens fail at the interface between affected and unaffected cells. A similar effect was observed by other researchers [39,66]. McGarva et al. [66] describe failure of Polymethylarylimide (PMI) foams parallel to the interface between compressed and original cells after joining to heated Polyamide based skins during double cantilever beam testing. In contrast PMI foams without compressed cells (joined to thermoset based skins) failed with a kinking crack propagation in the centre of the core. Akermo et al. [39] report on smooth failure near the core surface of Polypropylene (PP) foam cores featuring densified cells in the core surfaces after joining to heated PP based skins. Despite this, neither researchers specifically mention a lower strength value for the core in comparison to an original core.

Failure of the core in the boundary layer could be explained by the stiffness discontinuity between affected and original cells, which represents a sharp transition inducing stress concentration under load. While the stiffness discontinuity between compressed cells and original cells may depict a stronger transition than stretched cells to original cell, the performance of foam cores with compressed stress cells might be further reduced than the performance of cores with stretched cells. This could explain the higher tensile value of the specimens 310-125-2 and 320-125-2 where stretched cells are observed opposed to the tensile strength of the specimens 300-125-2 where compressed cells in the boundary layer are seen. Furthermore, weakening of the core of specimens having a core density of 110 kg/m³ could not be observed in chapter 5.7. This might be explained by the softer transition between affected and unaffected cells since the original core already features a high cell density. Raster electron microscopy of the failure areas did not reveal any additional explanation for failure in the interface between affected and original cells. Detailed studies on failure paralleling an interface in general are reported by Hutchinson et al. [192].

A similar phenomenon in the boundary layer structure can also be observed for the climbing drum-peel specimens, leading to increased peel strengths with increasing T_{Skin}, see Figure 69.

Although the tensile and drum-peel performance can be partially increased by increasing the skin temperature, it must be considered that the sandwich thicknesses lay significantly below the aimed thickness, which indicates that temperatures of 310 °C and 320 °C cause uncontrolled core collapse and lead to unreproducible results. Furthermore, several properties such as shear and compression strengths are not significantly improved by increasing T_{Skin}. Therefore, a skin temperature of 300 °C seems most reasonable for the manufacturing process.

6.3.2 Influence of core compaction distance ($d_{compaction}$)

The investigations reveal that the core compaction distance has a considerable influence on the mechanical properties of the sandwiches, as displayed in Figure 74. Again, all results are normalised to reference specimens 300-125-2.

The results clearly show the influence of the core compaction distance on all characterised mechanical properties of the sandwich structures. In the case of sandwiches manufactured with 1 mm core compaction distance, the skin-to-core bond strength is low and weaker than the core tensile strength itself. The low bond quality can be explained by insufficient contact of foam and core which is required for interdiffusion of the molecules, see chapter 5.5.1.

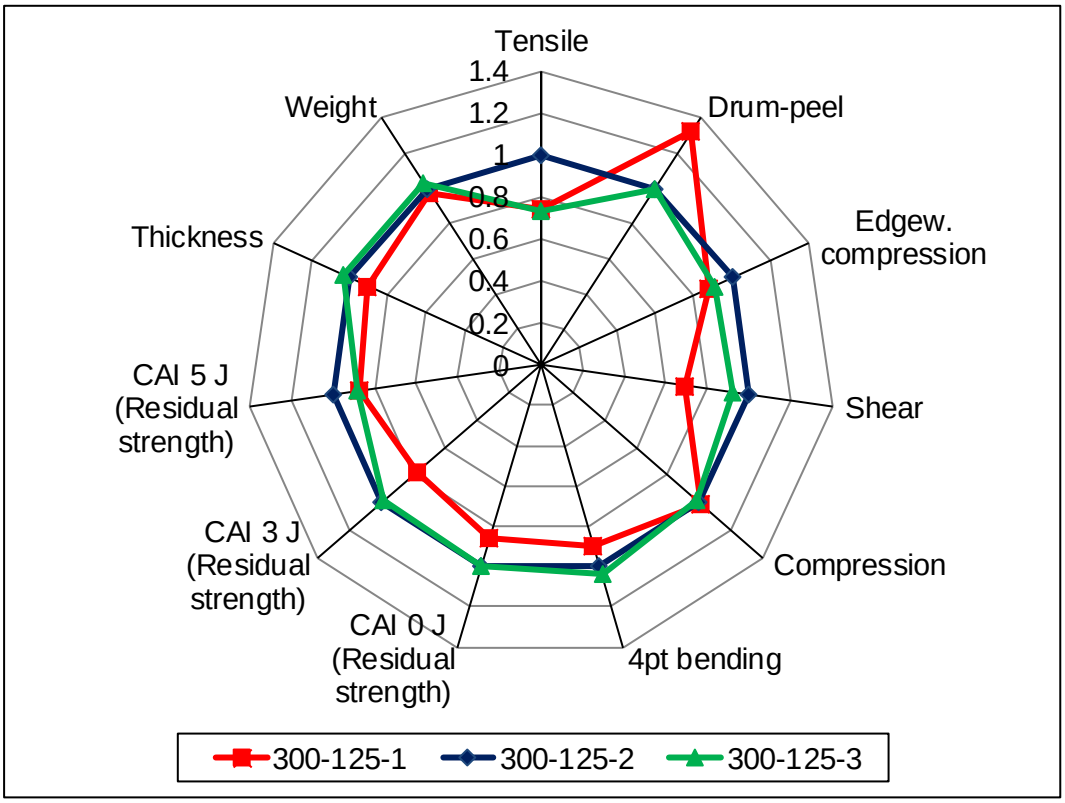


Figure 74: Influence of the core compaction distance on the mechanical properties

Due to heating the core slightly collapse (which occurs for all cases), but the skin cannot follow the core and keep contact due to the limited core compaction distance of 1 mm controlled by the mould stops. The sandwich thickness is measured to be 1.5 mm below S_{aimed} = 16.3 mm, which proves core collapse. In contrast, by applying $d_{compaction}$ of the 2 mm, the skin can further move into the core and keep contact. Therefore, $d_{compaction}$ of 2 mm leads to the aimed thickness. Figure 75 shows partial adhesive failure of the specimens manufactured with 1 mm compaction distance in comparison to pure boundary layer failure of specimens manufactured with 2 mm compaction distance, where the skin can follow the core collapsing, see Figure 71. Adhesive failure leads to a reduced measured tensile strength of specimens 300-125-1.

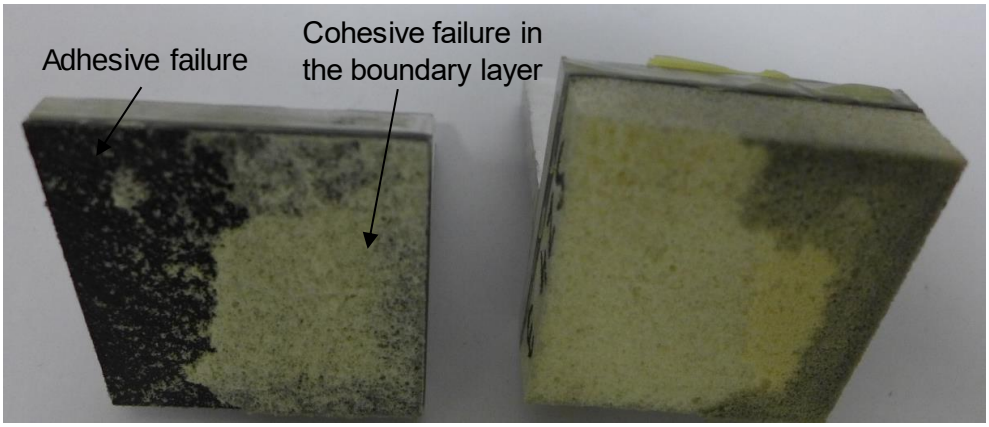
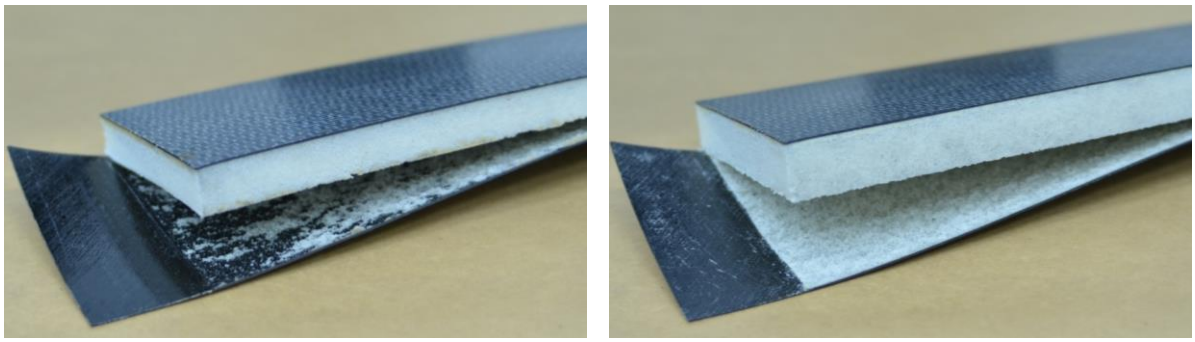


Figure 75: Adhesive and boundary layer cohesive failure of the specimens 300-125-1

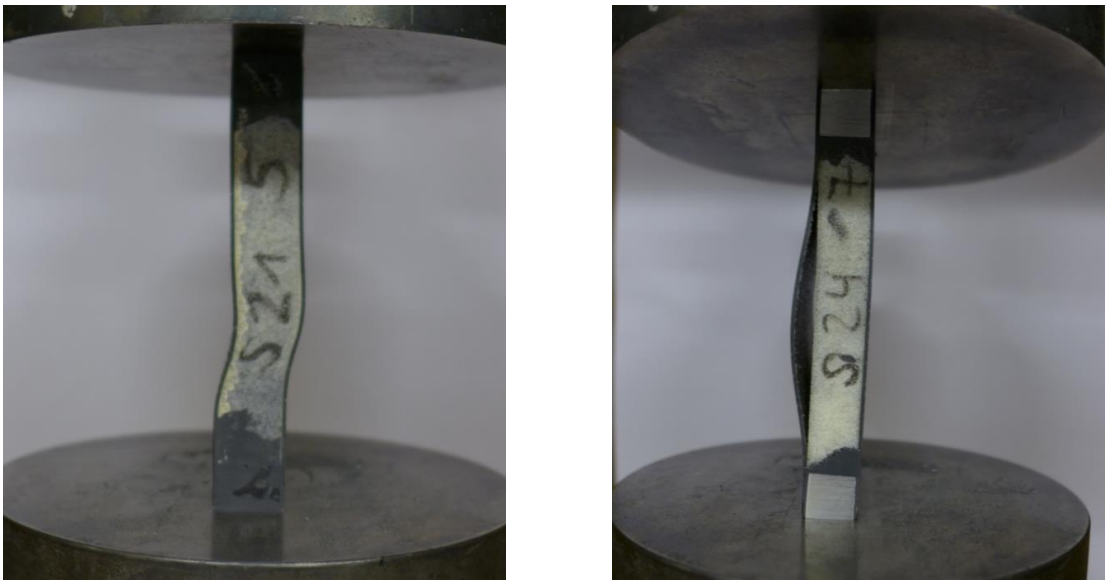
Even though the peel strength of the specimens manufactured with 1 mm core compaction distance is higher than of the specimen with 2 mm and 3 mm core compaction distance, analysis of the failure mechanisms (Figure 76) shows the insufficient bond quality of the specimens 300-125-1 leading to partial adhesive failure. A reason for the higher peel strength, although adhesive failure occurred, might be that it takes more energy for the crack to propagate through interface and foam than for propagating along the pre-defined path in the boundary layer at the interface between compressed and original cells as observed for the specimens 300-125-2 and 300-125-3.



a) **b)**

Figure 76: Failure mechanisms as occurred during drum peel testing: a) Partial adhesive failure in series 300-125-1 and b) Cohesive boundary layer failure in series 300-125-2

The weak skin-to-core bond for specimens manufactured with 1 mm core compaction distance can also be observed during edgewise compression testing. While specimens manufactured with 2 mm and 3 mm core compaction distance buckle under load, skin separation is the main failure mechanism of the specimens manufactured with 1 mm, see Figure 77.



a) **b)**

Figure 77: a) Buckling of the structure during the edgewise compression test as occurred in the specimen series 300-125-2 and 300-125-3; b) Skin separation during the edgewise compression test as occurred in series 300-125-1

Specimens manufactured with 3 mm core compaction distance show also deviating properties regarding tensile, shear or edgewise compression performance (Figure 74), albeit similar failure modes as for specimens manufactured with $d_{compaction}$ = 2 mm occur. By increasing the core compaction distance to 3 mm, the performance regarding tensile strength is significantly reduced in comparison to the tensile strength of specimens with 2 mm core compaction distance. An explanation might be again the stiffness discontinuity between affected and original cells which causes stress concentrations and thereby core failure. Figure 78 shows that the boundary layer cells of specimens 300-125-3 are compressed within a layer of approximately 400 µm, which is a comparable affected boundary layer to the specimens manufactured with 2 mm compaction distance, see Figure 72. This means that the cells of the specimens 300-125-3 are densified to a higher extent in the boundary layer than the cells of the specimens 300-125-2, since the core is compacted for 3 mm instead of 2 mm. This leads to the assumption that the higher densification of cells in the boundary layer of specimens 300-125-3 leads to a sharper stiffness discontinuity between affected and originals cells in comparison to the stiffness discontinuity resulting from 2 mm core compaction. Following, higher stress concentrations lead to a decrease of the tensile performance of the core.

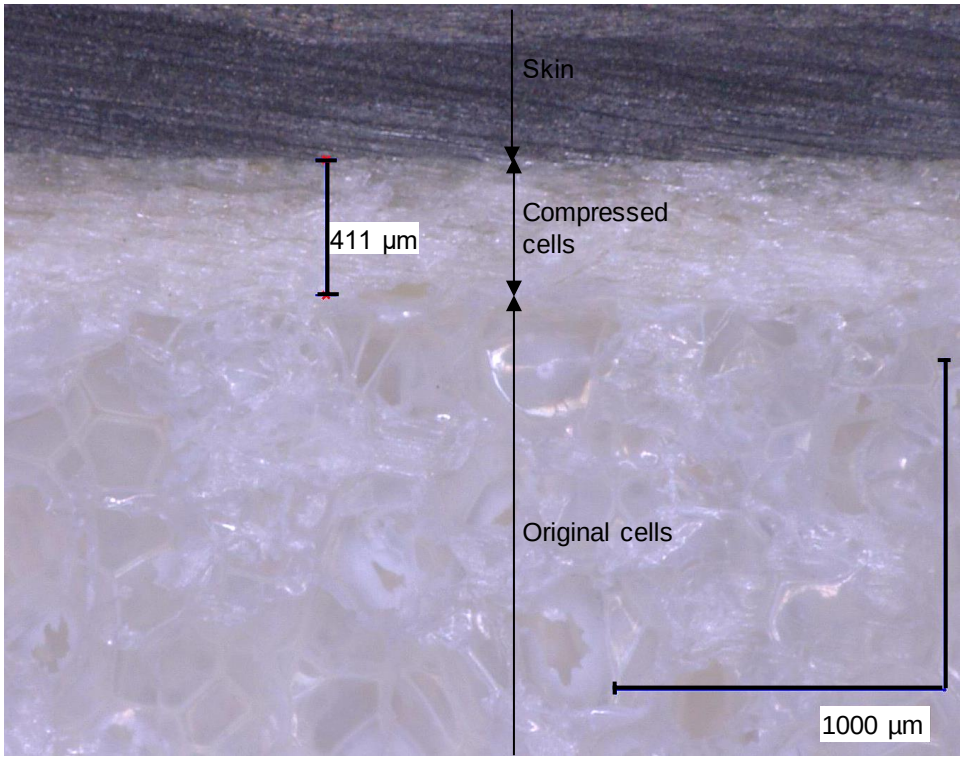


Figure 78: Cell structure of the specimens 300-125-3 (without potting resin)

Furthermore, the testing results show that a higher core compaction distance additionally leads to a reduction of shear strength, see Figure 74.

In order to eliminate doubts that the decrease of the sandwich performance or core performance in the case of the specimen 300-125-3 is affected by an insufficient fusion bond between skins and core, but rather caused by a higher cell compression, additional trials that aim to compact the core cells locally, are conducted. Therefore, additional trials that compress the core surface cells without fusion bonding the core to a skin are performed. By doing so,

PEI foam cores (60 kg/m³) are compacted 2 mm and 3 mm in the boundary by means of a 300 °C heated aluminium plate (so no fusion bonding to CF/PEEK skins takes place) and characterised by tensile and shear testing. Figure 79 exemplarily shows the compressed cells (without fusion bonding) at the core surface for a core compaction of 2 mm.

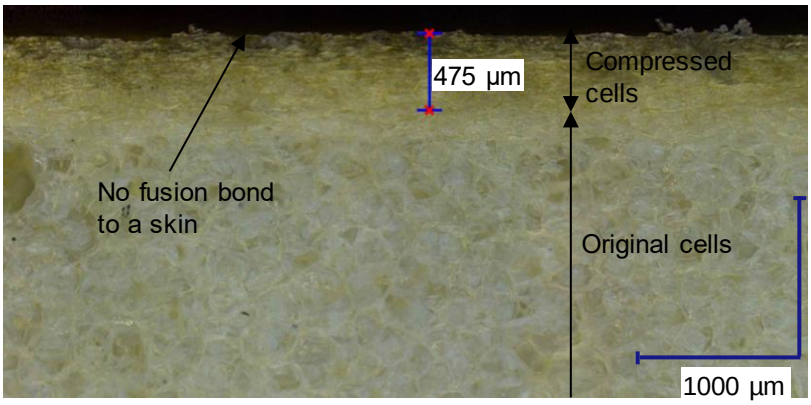


Figure 79: Compacted cells in the boundary layer of specimens without fusion bonding (without potting resin)

The comparison of the normalised tensile strength (normalised to the tensile strength of the initial untreated core) of the compacted foams to the initial foam shows that compacting the foam 2 mm (specimens 300-2), 3 mm (specimens 300-3) respectively, leads to a significant decrease of the tensile strength, see Figure 80a. Furthermore, the compacted foams fail cohesively in the boundary layer, while the initial foam fails cohesively within the core centre. These results confirm the assumption that foam compaction leads to a weakening of the foam caused by an interface between affected and original cells. The comparison of the normalised shear strength of the compacted foams to the initial foam shows that foam compaction (2 mm and 3 mm) leads to a slight decrease of the shear strength, see Figure 80b. However, a difference in the failure modes, which is cohesive failure, cannot be observed. A reason for the decreased shear strength of the compacted foams could also be stress concentration at the interface between affected and original cells, which leads to crack initiation under lower loads.

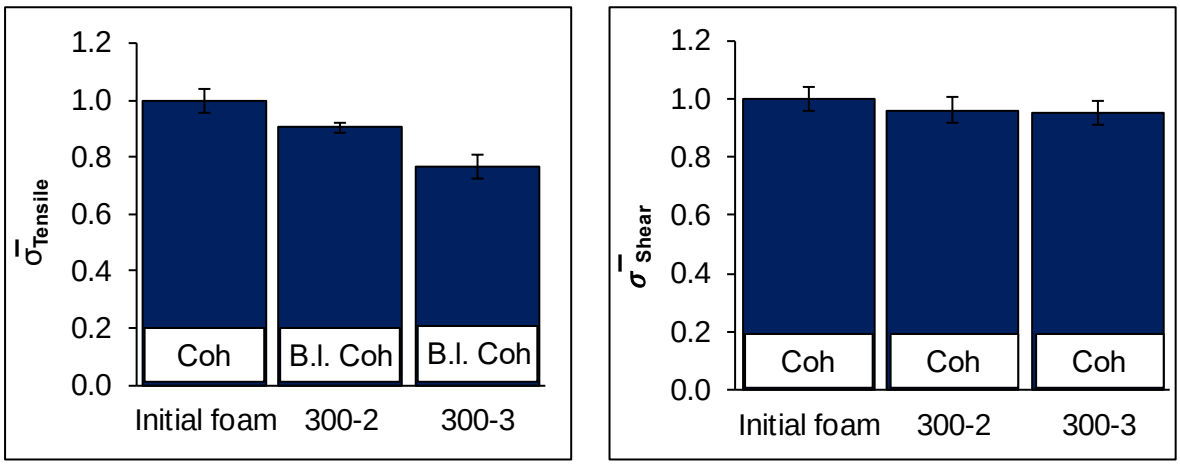
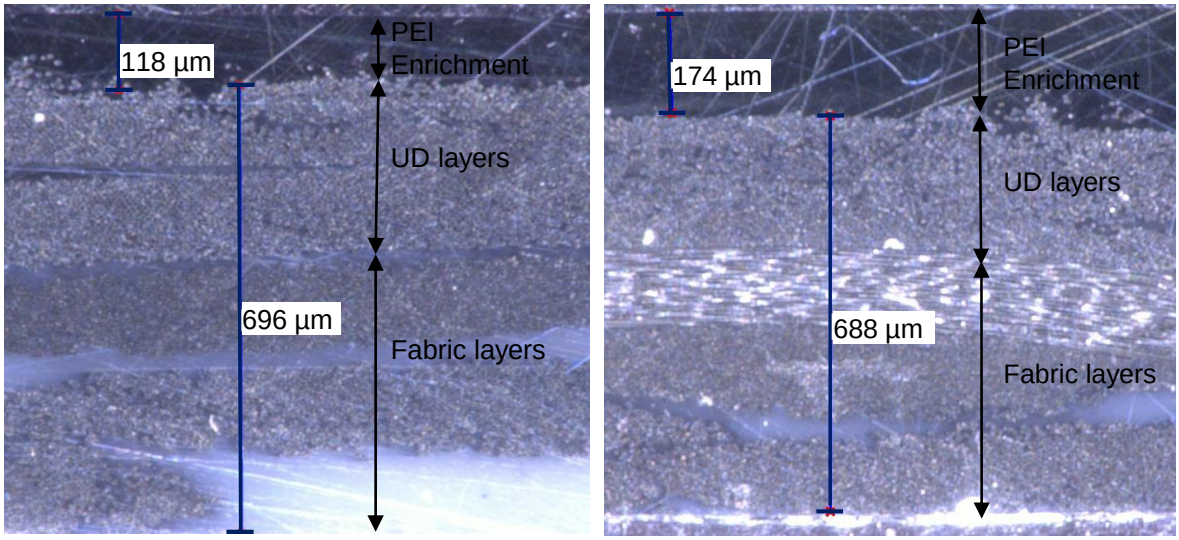


Figure 80: a) Tensile strength results of initial and compressed PEI foam cores (60 kg/m³) and b) Shear strength results of initial and compressed PEI foam cores (60 kg/m³)

Finally, it has to be mentioned that core compaction additionally increases the areal density of the sandwiches and thereby negatively influences the performance-to-weight ratio. A core compaction of 3 mm in comparison to a core compaction of 2 mm increases the weight by approximately 5 %. Summing-up, 2 mm compaction distance seem to be the optimal compaction distance in this study.

6.3.3 Influence of the PEI film thickness (h_{PEI})

In Figure 81 skins enriched with different PEI layer thicknesses (125 µm and 175 µm) are displayed. The difference of the PEI film thickness on the skin surface can be clearly seen.



a) **b)**

Figure 81: Skins enriched with a) 125 µm PEI film (300-125-2) and b) 175 µm PEI film (300-175-2)

Figure 82 illustrates the performance of TPC sandwiches manufactured with different PEI film thicknesses on the skin surfaces. The results are again normalised to the performance of reference specimens 300-125-2.

The results show that most properties are not significantly influenced by increasing the PEI film thickness. In addition, specimens manufactured with different PEI film thicknesses show equal failure modes. An explanation of the slight increase of the tensile, peel and 4pt- bending strength of the specimen 300-175-2 might be an improved wetting which leads to a better skin-to-core bond. Specimens of both series fail cohesively within the boundary layer, though a difference within the core cell structure cannot be observed. However, increasing the PEI film thickness to 175 µm increases the areal density by approximately 5%, which affects the performance-to-weight ratio negatively.

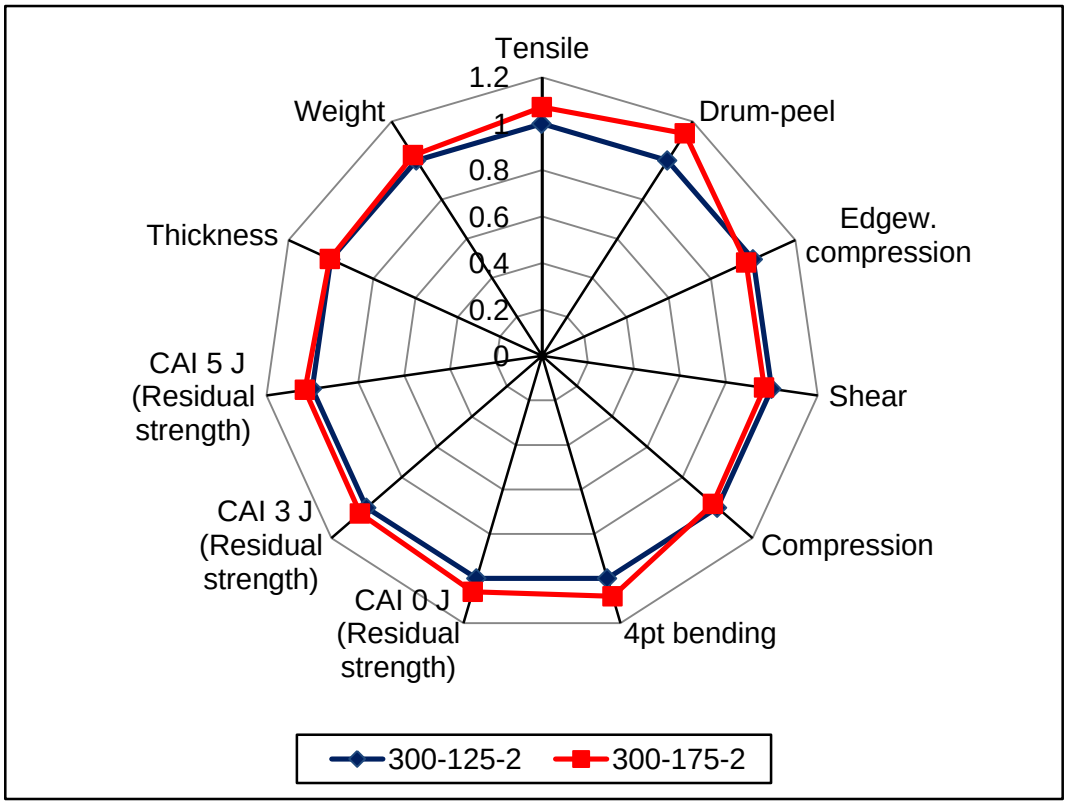


Figure 82: Influence of the PEI film thickness on the mechanical properties

6.4 CONCLUSION

This chapter presents a detailed performance characterisation of the developed sandwiches depending on several process parameters. The investigations show that the proposed process window (concerning skin temperatures) resulting from chapter 5 mostly enables a fusion bond strength between skins and core that exceeds the core strength and leads in most cases to cohesive failure of the core. The high skin-to-core bond strength is mainly shown by tensile and drum-peel testing. However, in the case of a minimal core compaction distance of 1 mm in combination with skin temperatures in the range of 300 °C – 320 °C, contact between skins and core cannot be guaranteed, leading to an insufficient bond and low overall performance of the sandwiches.

Moreover, analysis of the core structure reveals that the processing parameters significantly influence the thermoplastic core cell structure in the boundary layer and thereby affect the core performance. Mainly the tensile and drum-peel strength but as well shear properties are affected by the change of the cell structure. At skin temperatures of 300 °C the core cells in boundary layer are compressed, while higher skin temperatures (320 °C) cause core collapsing in the core centre, which leads to cell stretching of the cells in the boundary layer. Furthermore, a higher core compaction distance (3 mm) causes a higher cell densification in the boundary layer. A change of the core cell structure leads to a weakening of the core and failure predominantly occurs in the interface between affected and original cells. Failure of the core in the boundary layer could be explained by the stiffness discontinuity between affected and original cells, which represents a sharp transition inducing stress concentration under load.

While the stiffness discontinuity between compressed cells and original cells may depict a stronger transition than stretched cells to original cell, the performance of foam cores with compressed stress cells might be further reduced than the performance of cores with stretched cells. Besides the mechanical performance, by also assessing the manufacturing reproducibility and taking the areal weight into account, specimens manufactured with T_{Skin} = 300 °C, $d_{compaction}$ = 2 mm and h_{PEI} = 125 µm show the best performance and characteristics.

7. PERFORMANCE AND MANUFACTURING CYLE TIME EVALUATION

The investigations, presented in the previous chapter, show the influence of several processing parameters on several mechanical properties of carbon fibre reinforced Polyetheretherketone skin and Polyetherimide foam core (CF/PEEK-PEI) based sandwiches and reveal that specimens manufactured with T_{Skin} = 300 °C, $d_{compaction}$ = 2 mm and h_{PEI} = 125 µm feature the best overall performance. However, until now it is not possible to draw any conclusions if the developed TPC sandwiches fulfil the envisaged requirements for possible applications and if they show advantages in comparison to-state-of-the-art sandwich structures.

Therefore, this chapter presents a performance and manufacturing cycle time evaluation of the developed TPC sandwich structures. The evaluation process is illustrated in Figure 83. In a first step, the CF/PEEK-PEI based sandwiches are compared to state-of-the-art honeycomb sandwiches. In order to have an additional comparison to a foam based sandwich, sandwich structures based on Polymethacrylimide (PMI) foam cores and manufactured by liquid composite moulding (LCM) are additionally taken as a reference. LCM technologies offer the possibility of producing monolithic composite parts and composite sandwich structures of high quality, while reducing production and investment costs compared to prepreg technology. Today, novel infusion technologies enable the production of composite structures, which feature a similar quality to that achieved with prepreg technology [193,194]. Therefore, this technology also seems to be promising and attractive for producing sandwich structures that can substitute costly prepreg-Nomex® sandwiches. The foam based sandwich structures in this study are manufactured by resin transfer moulding (RTM). The RTM process allows higher pressures leading to a speeding up of the infusion process in comparison to other infusion technologies such as vacuum assisted infusion processes (VAP). Moreover, due to the double-sided formative mould, more reproducible parts with smaller tolerances and part thicknesses can be achieved [195].

In a second step the results are evaluated according to the given requirements.

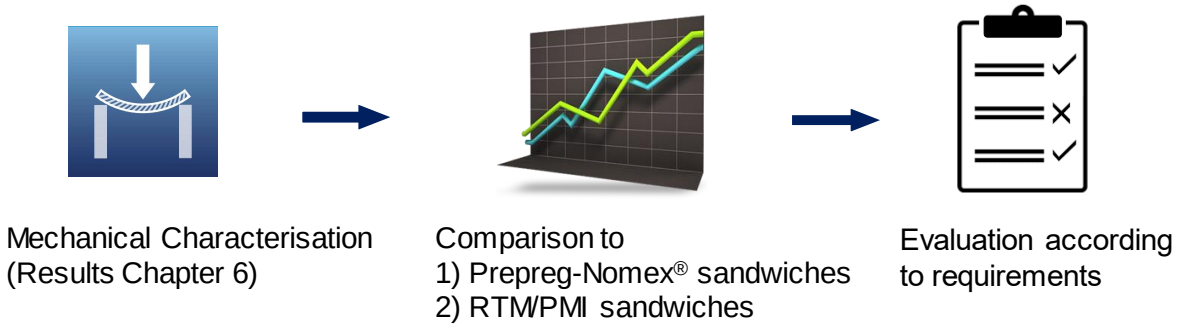


Figure 83: Approach for evaluation of TPC sandwiches

7.1 MATERIALS

A typical prepreg-Nomex® sandwich structure for helicopter applications is taken as the state-of-the-art sandwich structure reference. The skins are made by stacking three epoxy based prepreg plies (Hexcel Corporation, USA). The prepreg plies consist of a satin fabric with a fibre areal weight of 220 g/m². The fibre volume content amounts to 55 %. For the core a Nomex®

honeycomb (Euro-Composites® S.A., Luxembourg) featuring a density of 48 kg/m³ is chosen. The height of the core material is 15 mm. The skins are adhesively bonded by means of an epoxy based film (Cytec industries Inc, USA) in an autoclave process.

The skins for sandwiches manufactured with RTM consist of three plies of a plain fabric (Hexcel Corporation, USA), which are stabilised on both sides by 5 g/m² binder. The plain fabric is characterised by the use of 12K spread carbon fibre tows, so that undulations are reduced. The fabric's areal weight is 220 g/m². An epoxy based thermoset (Hexcel Corporation, USA) is used as matrix resin. Epoxy based resins are common for aviation applications and often used for infusion technologies since they feature a high glass transition temperature of about 183 °C. For the core, PMI foams (Rohacell®) with a densities of 63 kg/m³ by Evonik Industries AG, Germany are used. The foams feature closed cells and show a high elongation at break. A foam height of 15 mm is chosen. In Table 21 details on the three sandwich structures are presented. The material and sandwich dimensions are aligned to each other as good as possible. Nevertheless, due to material availability and different manufacturing process setups deviations have to be accepted. Furthermore, the TPC sandwiches require the application of two unidirectional (UD) reinforcement plies instead of one fabric ply for the skin setup to avoid interdiffusion of the PEI surface layer into the structures.

Table 21: Details on sandwich structures

Skins	Fibre reinforcement	Fabric	Fabric	Fabric + UD
	Matrix polymer	Epoxy	Epoxy	PEEK
	Number of plies	3	3	5
	Ply sequence	[±45;0,90;±-45]	[±45;0,90; ±45]	[+45,-45;0,90;±45]
	Skin thickness	~0.62 mm	~0.625 mm	~0.69 mm
	Fibre areal weight	660 g/m²	660 g/m²	730 g/m²
	FVC	55 %	~ 60 %	~ 60 %
	Adhesive film	170 g/m²	/	160 g/m²
Core	Core structure	Honeycomb	Foam	Foam
	Core material	Aramid/Phenolic	PMI	PEI
	Core density	48 kg/m³	63 kg/m³	60 kg/m³ (76 kg/m³ after compaction)
	Core height	15 mm	15 mm	19 mm (Compacted to 15 mm)

7.2 EXPERIMENTAL

7.2.1 Specimen preparation - Prepreg/Honeycomb Sandwiches

First the prepregs and adhesive films are cut to the required dimensions. Next, the honeycomb core is shaped by machining. Usually sealing and stabilisation of the Nomex® core is required, though for flat (two-dimensional) panels such as are tested here these steps can be spared. However, for a realistic assessment these manufacturing steps need to be considered. Then the adhesive films and prepregs layers are stacked together with the core.

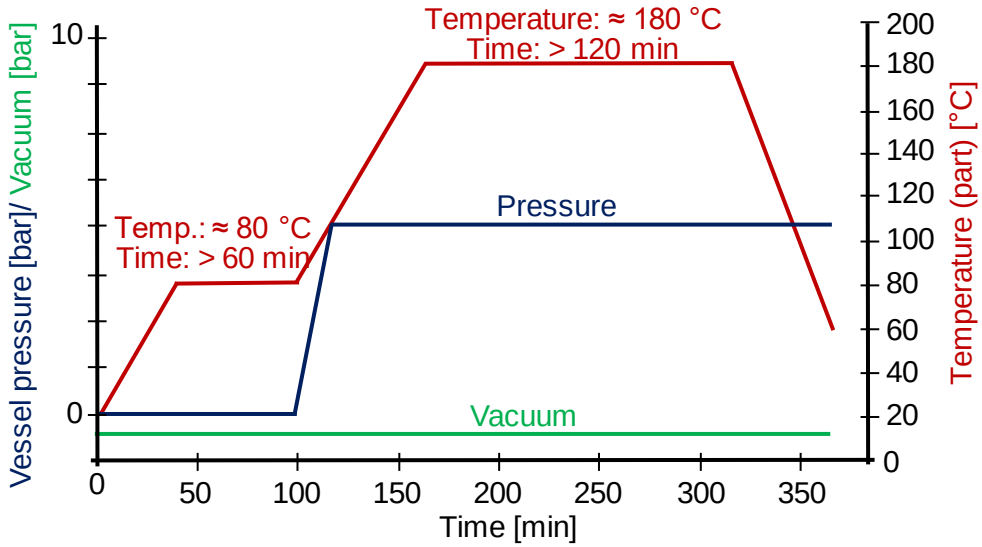


Figure 84: Autoclave cycle for manufacturing of Nomex® based sandwiches

For the autoclave processing a vacuum setup must be installed. The whole setup is heated to approximately 180 °C and consolidated under a pressure of approximately 10 bars for 6 hours in an autoclave, see Figure 84. After cooling, the sandwich can be released and post processed. Due to the vacuum setup, post processing such as cleaning of the facilities is required.

7.2.2 Specimen preparation - RTM/PMI foam sandwiches

In a first step, fabrics are cut, placed manually, powdered with binder and kept in position by means of a vacuum bag. Then the preform is stabilised in an oven for approximately 20 min at 120 °C to activate the binder. Subsequently, resin and mould are heated. Then preform and core are placed into the mould. By means of 0.3 MPa pressure and a pre-heating temperature of 140 °C the matrix resin is injected, before being further heated to 180 °C for curing. Finally, the mould is cooled down for de-moulding. In Figure 85 the process cycle is displayed, which takes around 3.5 hours. Moreover, labour time for installation of the tool and post processing has to be considered.

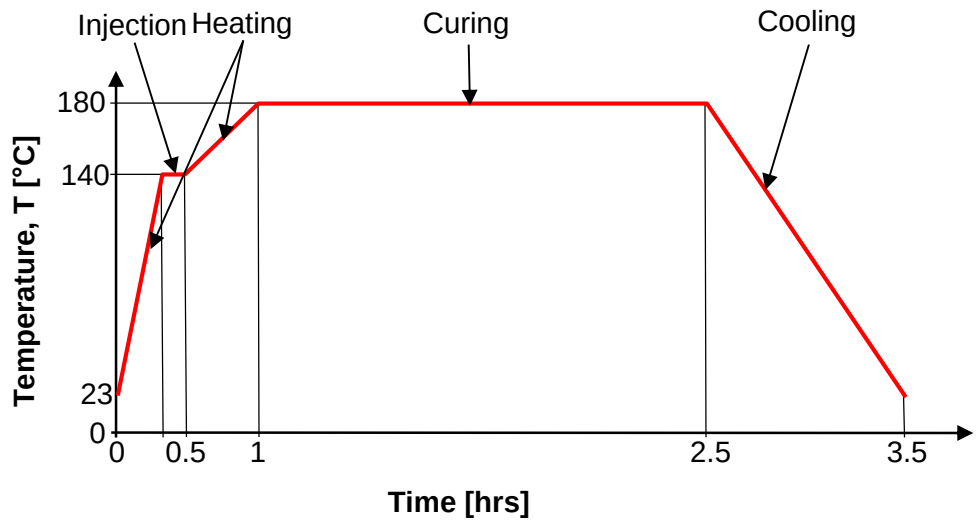


Figure 85: Cycle time for the RTM process

7.2.3 Test setup

Tensile, climbing drum-peel, shear, compression, bending and CAI testing is performed with the reference sandwiches similar to the characterisation of the CF/PEEK-PEI foam sandwiches in chapter 6.2.2. For a full description see chapter 6.2.2.

7.3 COMPARISON TO REFERENCE SANDWICH STRUCTURES

7.3.1 Comparison of mechanical performance

Figure 86 shows the performance comparison of the CF/PEEK-PEI foam sandwiches according to parameter set 300-125-2 and the prepreg-Nomex® and PMI based sandwiches. The comparison shows significantly superior performance of the prepreg-Nomex® (PH) based sandwiches concerning all properties. Furthermore, the comparison reveals that the RTM-PMI (RTM63) sandwich structures also show a slightly better performance in comparison to the CF/PEEK-PEI foam sandwiches (300-125-2). The sandwich performance differences are caused primarily by the performance of the core, since failure during tensile, shear and compression testing occurs mostly in the core. This highlights the superior performance of the honeycomb structure in comparison to the foam structure, as discussed in chapter 1.

However, it is surprising that the thermoplastic based sandwiches (300-125-2) do not show a significantly better or better performance after impact, since thermoplastic materials are in general considered to be tougher and display better damage behaviour. Overall, the obtained strength results of thermoplastic sandwiches are significantly lower than that of the other sandwiches, see Figure 86. In order to show the decrease of the strength after impact, Figure 87a visualises the knockdown factor (compression strength normalised to the strength without impact (0J)) of the sandwiches after impacting with different impact energies (3J, 4J, 5J). The comparison of the knockdown factor shows a lower decrease of the strength after impact of the TPC sandwiches (300-125-2) in comparison to the RTM63 sandwiches. However, by comparing the decrease of the strength results to the prepreg-Nomex® based sandwiches, no advantage of the use of thermoplastic material can be identified. Figure 87b additionally

indicates the penetration depth ($d_{penetration}$) of the falling weight into the sandwich structures, which also shows the intermediate performance of the TPC sandwiches.

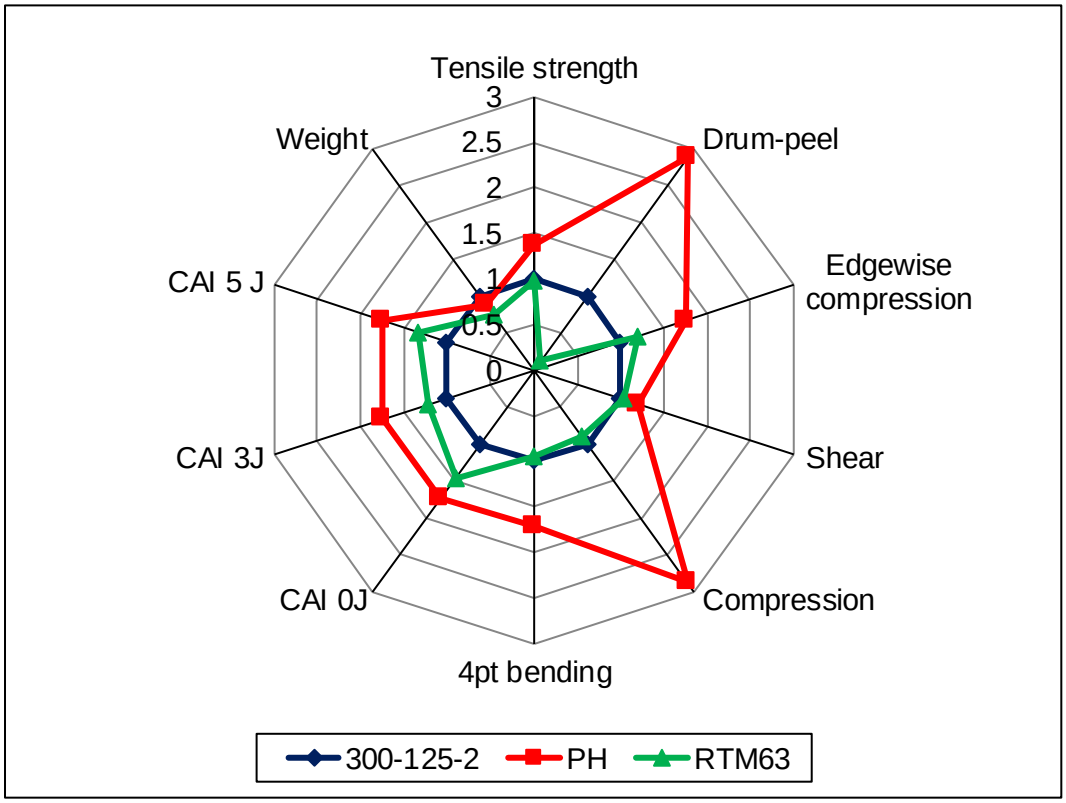
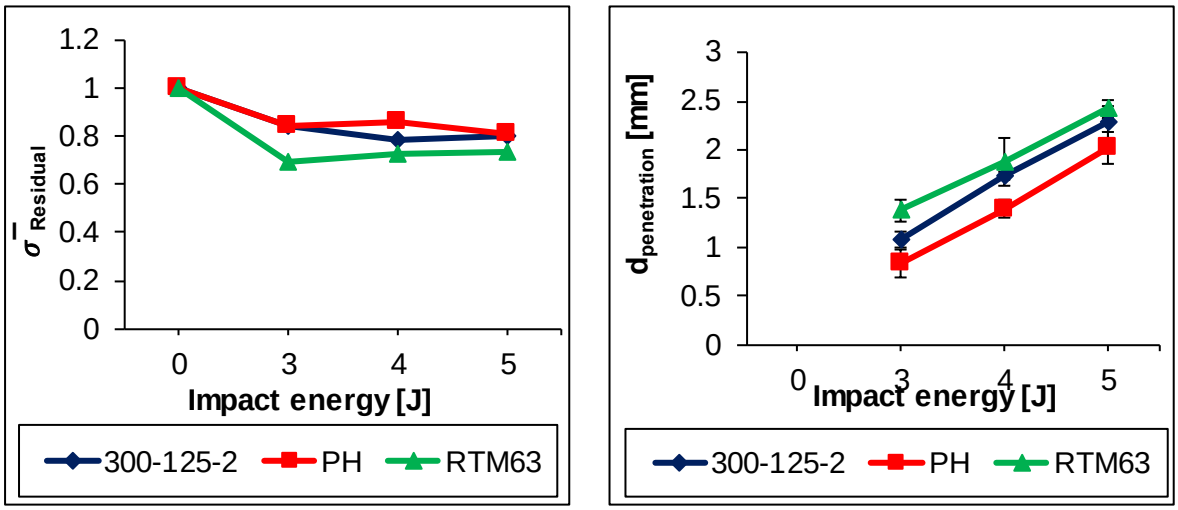


Figure 86: Comparison of the performance of the three different sandwich structures

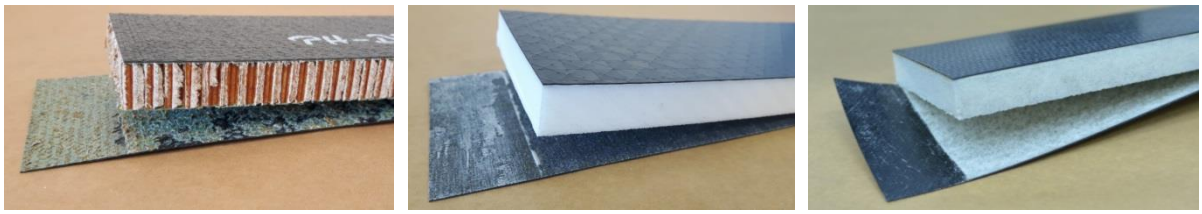


a) **b)**

Figure 87: Comparison of a) Normalised residual strength of the different sandwich structures after impact and b) Penetration depth of the impact weight into the different sandwich structures

Besides the lower mechanical performance concerning most properties, the mechanical characterisation shows that the CF/PEEK-PEI foam sandwiches feature a strong skin-to-core bond, leading in most cases to failure within the core. In comparison, Nomex® based and PMI

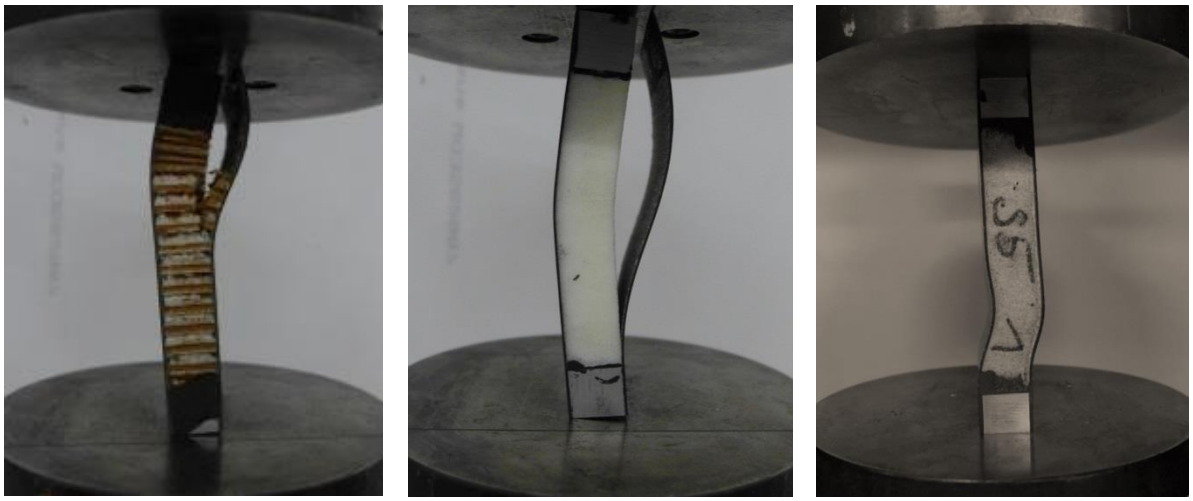
foam based sandwich specimens fail mostly within the interface. Figure 88 shows the failure mechanisms for each material system which occur during climbing drum-peel testing. The comparison shows that in the case of the PH and RTM63 specimens the skin-to-core bond is the weakest link (Figure 88a and Figure 88b), while for the CF/PEEK-PEI foam sandwiches (300-125-2) the core represents the weakest link, see Figure 88c.



a) **b)** **c)**

Figure 88: Failure mechanism during drum-peel testing: a) Adhesive failure of the PH specimens, b) Adhesive failure of the RTM63 specimens and c) Boundary layer failure of the 300-125-2 specimens

Similar failure behaviour can be observed during testing according to other standards such as edgewise compression testing or bending testing. Figure 89 shows the different failure mechanisms which occur during the edgewise compression testing. Skin separation is the common failure mechanism for the PH and RTM63 sandwiches (Figure 89a and Figure 89b), while buckling of the whole sandwich is the dominant failure mechanism for the 300-125-2 specimens, see Figure 89c.



a) **b)** **c)**

Figure 89: Failure mechanisms during edgewise compression testing: a) Skin separation and core rupture for the PH specimens, b) Skin separation for the specimens RTM63 and c) Buckling of the whole sandwich for the specimens 300-125-2

Summarising, the characterisation reveals that the PEI foam core weakens the TPC sandwiches as it features properties which are significantly below the properties of Nomex® and PMI cores such as shear modulus (~ - 40 %) or compression strength (~ - 40 %).

7.3.2 Comparison of areal weight

Remarkably, PMI foam based sandwiches (RTM63) have the lowest areal weight even though the foams have a higher density than the Nomex® core, see Figure 86. The weight decrease

of approximately 24 % related to the thermoplastic based sandwiches (300-125-2) can be explained by the lack of adhesive films for the RTM processed sandwiches. The joint between skins and core is created by the resin flow into the surface cells of the foam. Details on the areal weights are shown in Table 22. The table shows clearly that thermoplastic sandwiches feature the highest areal density of all structures. The high areal density is caused by compression of the core resulting in a higher core areal weight. Furthermore, the use of two UD layers in the skins, each having a fibre areal weight of 140 g/m², increases the weight compared to the use of one fabric ply with 220 g/m². In addition, the use of the PEI surface layer with ~160 g/m² leads to an increase of the areal weight, even though it is a slight weight advantage in comparison to the epoxy based adhesive films (~ 170 g/m²) for the prepreg-Nomex® sandwiches. Nomex® based sandwiches show an approximately 15 % lower weight than the thermoplastic sandwiches.

Table 22: Comparison of areal weights

Areal weight	300-125-2	PH	RTM63
Skins [g/m²]	2280	2100	1916
Adhesive layers [g/m²]	320	340	/
Core (15mm height) [g/m²]	1140	720	945
Total [g/m²]	3740	3170	2861
Decrease to 300-125-2 [%]	/	-15	-24

7.3.3 Comparison of manufacturing cycle times

In Figure 90 the cycle times for the production of the sandwiches by means of the three different approaches are displayed. The comparison shows that by application of thermoplastic materials or by application of the RTM process the cycle time can be significantly decreased in contrast to the manufacturing of prepreg-Nomex® sandwiches. The infusion approach leads to a cycle time reduction of 24 %. By applying thermoplastic materials, a cycle time reduction of 46 % can be achieved. The results are based on laboratory trials, which means that most steps are performed manually and some deviations are expected when the approaches are adapted for a serial production. In addition, some manufacturing steps such as cutting fabric plies or shaping the core are assumed to be equivalent for all approaches. Furthermore, the flat 2D Nomex® sandwich panels do not require sealing and stabilisation. For more complex shapes, additional time for the Nomex® core treatment has to be considered, which leads to an even higher time reduction for foam based sandwiches.

By taking a deeper look at the single manufacturing steps, it can be noticed that for the prepreg and the RTM approach the “manufacturing process” is the most time-consuming step. During this step, the resin must cure at a high temperature. For the TPC approach, the sandwich “manufacturing process” is done in a couple of minutes, since the skins only have to be heated, stacked with the core and joined under pressure. The fusion bonding process, performed non-isothermally in this case, takes place in a matter of seconds. For the TPC approach the

consolidation of the skins is the most time-consuming step, since the material, placed in a heavy metal tool, has to be heated up to 375 °C, held for some minutes and then cooled down.

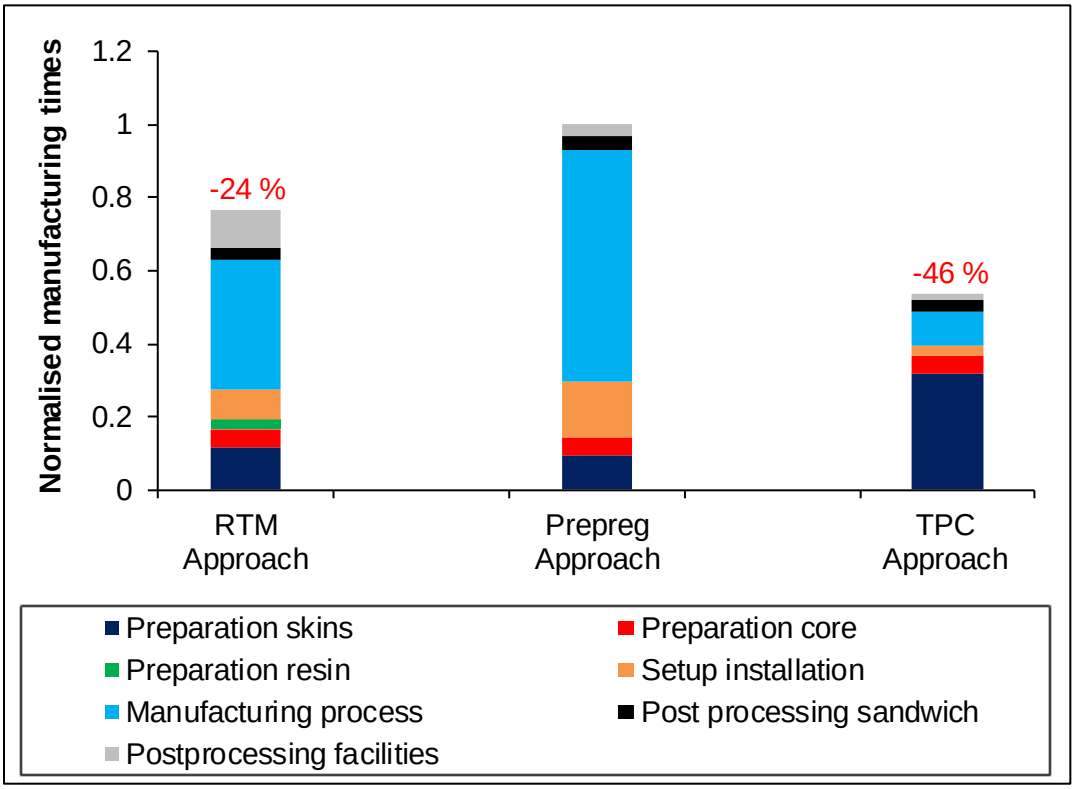


Figure 90: Comparison of manufacturing cycle times

7.4 PART COST AND LIFE CYCLE COST ANALYSIS

In the previous chapter, it is shown that thermoplastic sandwich structures offer the opportunity to be manufactured in significantly shorter cycle times than state-of-the-art sandwiches and RTM/PMI foam based sandwiches. Short manufacturing cycle times contribute to the decrease of production cost and minimise the final part cost, which is the global motivation of this thesis. However, besides the manufacturing cycle time several other parameters such as material cost, machine investment, machine operating cost need to be considered for a complete cost analysis. At this stage of the development, it is difficult to work out a realistic business case and to calculate the part cost of a thermoplastic sandwich structures. Realistic production scenarios, material prices and machine operating cost for a serial production are not available. Therefore, Figure 91 gives only a rough estimation of sandwich part cost, which is based on a laboratory scenario including material cost (including auxiliary materials), labour cost (possibility of parallel labour steps is neglected) and cost for machinery investment. The cost estimation is calculated for one square metre sandwich structure (setup and dimensions according to the previous chapters) and based on the assumption that two parts per day (maximum capacity of an autoclave for prepreg-Nomex® sandwich manufacturing) will be manufactured over the asset depreciation range of machines (seven years). Figure 91 shows that a decrease (~ -32 %) of the overall part cost is possible by the application of thermoplastic materials. Even though thermoplastic

materials are costlier than state-of-the-art thermoset materials (~ +50 %), the significantly shorter manufacturing cycle times lead to lower total part cost. Furthermore, less machine investment (no autoclave) is needed to manufacture thermoplastic sandwich structures.

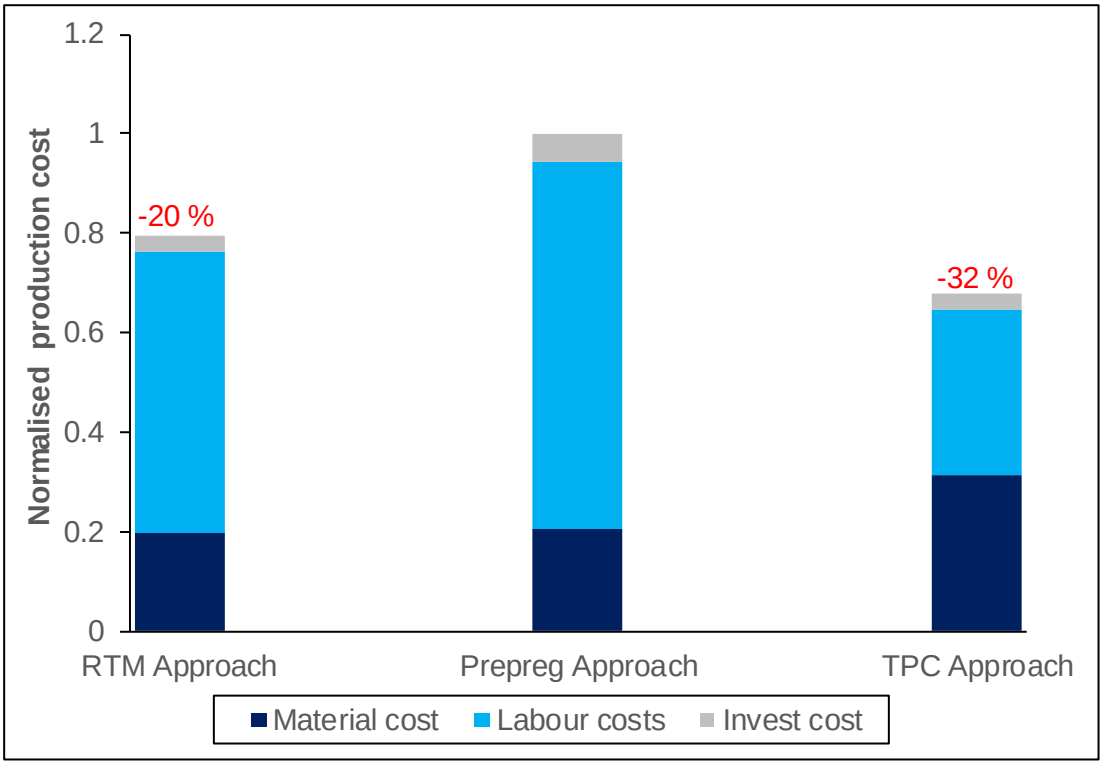


Figure 91: Normalised production cost of one square meter sandwich

In addition, it is assumed that the life cycle cost of thermoplastic sandwich structures will be significant lower than the life cycle cost for prepreg-Nomex® sandwiches, since less maintenance during service will be necessary and recycling after service will be possible. However, a realistic life cycle cost analysis exceeds the scope of this work.

7.5 EVALUATION ACCORDING TO REQUIREMENTS

In chapter 1.2 requirements concerning skin and core materials, processing conditions and HSE (Health, Safety and Environment) characteristics are presented to serve as a guideline for the materials selection and to evaluate the developed sandwich structures, which will be described in this section.

7.5.1 Evaluation according to performance requirements

Since sandwich structures are usually designed to carry shear loads caused by bending moments acting on the skins and to withstand compression loads when for example applied as floor panels, the compression and the shear strength are relevant properties for sandwich structures. Furthermore, the skin-to-core joint is of major importance to allow the force transfer from skins to core.

The material selection (chapter 4.1) showed that PEI foams having a density of 110 kg/m³ can fulfil these requirements concerning compression and shear strength. However, for the mechanical characterisation and comparison with other structures, foams with a density of

60 kg/m³ are used. The mechanical characterisation reveals that CF/PEEK-PEI foam sandwich structures with a 60 kg/m³ core feature a compression strength which is approximately 45 % below the required compression strength, while the shear strength is approximately 20 % the required 1.1 MPa. By applying a PEI foam core with a density of 110 kg/m³, it is assumed that the performance can be increased almost to the required values. However, by applying a core with a higher density, the weight will be further increased, which in the case of the 60 kg/m³ PEI foam core is already higher compared to state-of-the-art sandwiches.

The mechanical characterisation also reveals that the fusion bonded thermoplastic sandwiches possess a high skin-to-core bond strength compared to the PMI foam based sandwiches, which lays above the required peel strength by a factor of 2.65. Surprisingly, the thermoplastic sandwiches cannot fulfil the required residual strength after impact energy of 5 J. The achieved residual strength lays 15 % below the required value.

The PMI foam based sandwiches fulfil the requirements better because of the good performance of the core. However, the sandwiches show an insufficient peel strength which lies approximately 30 % below the required 0.8 N/mm.

7.5.2 Evaluation according to processing requirements

The investigated process is challenged by a cycle time below four hours. The comparison of the cycle times shows that the process time could be decreased up to 46 % in comparison to the state-of-the-art autoclave manufacturing process by application of thermoplastic materials. Nevertheless, the fusion bonding process cannot totally fulfil the defined process time of four hours. However, the process cycle time assessment is based on laboratory results, which means that several manufacturing steps such as cutting of fabrics or skin heating are performed manually or without industrialised processing abilities. Therefore, it assumed that the cycle time can be at least 20 % further reduced when implemented as a serial production process, which would result in the desired cycle time.

7.5.3 Evaluation summary

Table 23 presents a summary of the evaluation of the developed TPC sandwiches on basis of the specimens 300-125-2. The comparison of the requirements shows the enormous potential of the sandwich structures but highlights again, that the PEI foam (60 kg/m³) is the weak point of the sandwiches. By taking a PEI foam core with a higher density of 110 kg/m³ (which was initially selected according to the requirements), the comparison shows that it will be possible to fulfil the envisaged requirements. However, in the case of 110 kg/m³ PEI foam core further weight disadvantages have to be accepted.

Table 23: Summarising evaluation according to performance requirements

Criterion	Aimed values	TPC sandwiches with 60 kg/m³ PEI foam (300-125-2)	TPC Sandwich with 110 kg/m³ PEI foam (expected performance)
Skin thickness	0.5 - 5 mm	Yes	Yes
Fibre volume content	> 55 vol %	Yes	Yes
Skin glass transition temperature	> 140 °C	Yes	Yes
Core thickness	10 - 50 mm	Yes	Yes
Core density	≤ 110 kg/m³	Yes	Yes
Moisture uptake	< 2.1 %	Yes	Yes
Core glass transition temperature	> 140 °C	Yes	Yes
Compressive strength	> 1.4 MPa	No	Possible
Core shear strength	> 1.1 MPa	No	Possible
Skin-core peel strength	> 0.8	Yes	Possible
Residual compressive strength after impact (5J)	> 150	No	Possible
Processing temperature	< 400 °C	Yes	Yes
Target cycle time	< 4 h	No, yet possible as an industrialised process	Possible as an industrialised process
Media resistance against, Cleaning agents, etc.	Required	Yes, when covered with CF/PEEK skins	Yes, when covered with CF/PEEK skins
Painting		Yes	Yes
UV- resistance	Required	Yes	Yes
FST requirements	(UL-94 V-0)	Yes	Yes
Components to be avoided that are toxic, mutagenic, carcinogenic	Required	Yes	Yes
Recyclability, re-use	Aimed	Possible	Possible

8. FOAM REINFORCEMENT

As previously stated, the carbon fibre reinforced Polyetheretherketone skin and Polyetherimide foam (CF/PEEK-PEI) based sandwich structures show significantly lower performances than the reference sandwiches and do not fulfil the envisaged requirements in the case of the usage of a PEI core with a density of 60 kg/m³. This is mostly caused by failure of the PEI core, which represents the weak point of the developed thermoplastic composite (TPC) sandwiches. Furthermore, the CF/PEEK-PEI sandwich panels feature already a higher areal density in the case of 60 kg/m³ PEI foams than the thermoset-based reference sandwiches. On the other hand, CF/PEEK-PEI foam sandwiches can be fusion bonded in short cycle times and feature high skin-to-core bond strengths, two characteristics that are attractive for their application in future helicopter structures.

In order to improve the properties of the CF/PEEK-PEI foam sandwiches and to achieve the required characteristics without significantly increasing the areal weight by applying cores with a higher density (110 kg/m³), it seems useful to apply low density foam cores, which are reinforced to strengthen their performance. In doing so, the areal density will be also increased, but will be probably kept low in comparison to the application of higher density foam cores. Therefore, in this chapter a manufacturing approach is presented, in which thermoplastic foam core sandwiches are reinforced to improve their mechanical performance.

Firstly, the idea behind reinforcing of foam cores is explained and state-of-the-art-concepts are presented, see chapter 8.1. Secondly, two concepts suitable for TPC sandwiches are elaborated (chapter 8.2). Following these concepts, thermoplastic foam cores are reinforced prior to skin-to-core joining, see chapter 8.3 and 8.4. To evaluate the influence of the foam reinforcement on the mechanical properties, the sandwiches are mechanically tested in chapter 8.5.

8.1 BACKGROUND OF FOAM MODIFICATION

The main idea of foam reinforcement is to strengthen the foam core to improve the compression and shear performance by means of inserting pins/rods or stitched rovings. While the inserted elements bear the majority of the loads, the surrounding foam prevents them from buckling and contributes to transferring shear loads. The pins can be introduced into the foam and joined to the skins in different ways. Besides the improved sandwich performance, it has to be considered that foam modification increases the manufacturing costs or the material costs and the total areal density of the sandwich structure. Thereby, an optimum between cost and areal density increase versus improved performance need to be found.

Today, different foam reinforcing concepts for thermoset based sandwiches are available on the market. Aztex Inc. (Waltham, Mass., U.S.A.) developed the X-cor™ and K-cor™ sandwich structures where the foam is reinforced by pre-impregnated fibre reinforced pins, referred to as Z-pins [196]. The pins are introduced into the foam with ultrasonic support and bended afterwards or are directly connected to the skins. A bond between foam, pins and skins is achieved by curing all components together. Marascoro et al. [196] investigated the mechanical performance of PMI foams reinforced by Z-pins implemented in the foam core under different angles. Honeycomb core based sandwiches were taken as a reference. The investigation showed that the compression strength and modulus of the modified sandwiches could be significantly increased by the application of the Z-pins, though they were still below

the compression strength of honeycomb based sandwiches. Concerning the shearing properties, the shear modulus could only be slightly improved, while the shear strength of a honeycomb panel still exhibited almost double the value of modified foam sandwiches. In contrast to the honeycomb sandwiches, the X-cor™ and K-cor™ sandwich structures failed within the skin-to-core interface.

Another concept for reinforcing foam cores was introduced by Airbus, known as the tied foam core technology [197]. A dry carbon fibre roving is introduced into the core by stitching. The roving protrudes on both sides of the foam core and is later connected to skin-preforms. It is also possible to stitch the skin-preforms directly onto the foam core. The foam/skin-preform setup is then infused with resin by means of typical resin infusion processes such as the vacuum assisted process (VAP®) or the resin transfer moulding (RTM) process. During the process the skin-preforms as well as the foam reinforcing rovings are impregnated with the resin and cured with the result that a connection between the foam, skins and reinforcing roving is realised. Endres [197] showed that the performance of PMI foams is significantly improved with regard to tensile, compression and peel strength. The best results were achieved when the skin-preforms were directly stitched onto the foam core. For shear strength investigation, the core was additionally reinforced with rovings implemented under different angles (45°, 60° and 75°), with best results being achieved by the introduction of 45° rovings.

8.2 MODIFIED TPC SANDWICHES: CONCEPT DEVELOPMENT

The idea of reinforcing the core is adapted to full TPC sandwich structures. The concept of stitching rovings, which are subsequently infused with resin, is not possible for thermoplastic materials due to the high viscosity of the thermoplastic polymer. Thermoset pre-impregnated and partially cured rods were dismissed since the aim is to develop a full thermoplastic sandwich structure.

Therefore, various approaches were explored and evaluated with the goal of achieving the desired reinforcement of the core while maintaining the advantages of the TPC process.

8.2.1 Initial Concept

One of the most important advantages of thermoplastic materials is the possibility that the materials can be softened or melted by the input of heat (or solvents), allowing the material to be reversibly reshaped or fusion bonded. The latter mechanism is already used during the manufacturing process of the TPC sandwiches, consisting of CF/PEEK skins and the PEI foam core in this study. During skin-to-core joining, energy (heat) is transferred from the skins into the foam core surface by heat conduction which ensures softening of the foam core material. The principle of softening the polymer to be joined by heat conduction from the skins with a following fusion bond process shall be adapted to the reinforced foam cores. In a first step, PEI pins of a length greater than the core's thickness are mechanically introduced into the foam core with the result that the pins protrude on both sides of the foam core, see Figure 92. The pins stick loosely in the foam core and are held in place within the foam core by friction. Placing the heated skins on the reinforced foam brings them in contact with the protruding ends of the rods first and thus leads to melting and compressing the rods until the skins additionally come in contact with the foam, leading to a softening of the core surface. By softening or melting the pins' ends as well as the foam core surface, a fusion bond between skins, pins and core is created. However, pre-trials show that the amount of energy supplied

by the pre-heated skins is insufficient to melt the protruded pin ends with the result that they are compressed inside the foam core. Thus, during processing the pins buckle under load and therefore this initial approach is not pursued further. Based on the experience gained with the initial concept, two adapted concepts are developed and further investigated, where the introduction of pins at various angles is applicable.

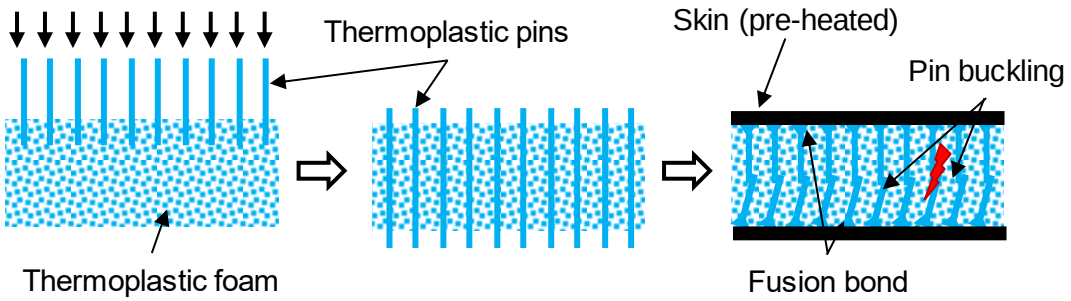


Figure 92: Schematic illustration of the initial concept of TPC foam reinforcement

8.2.2 Concept 1

In order to avoid pin buckling, pins of a length smaller than the foam thickness are used. However, the pins must feature a length greater than or at least equal to final core thickness, in order to come into contact with the skins during the fusion bonding process, to allow joining of the pins to the skins, see Figure 93.

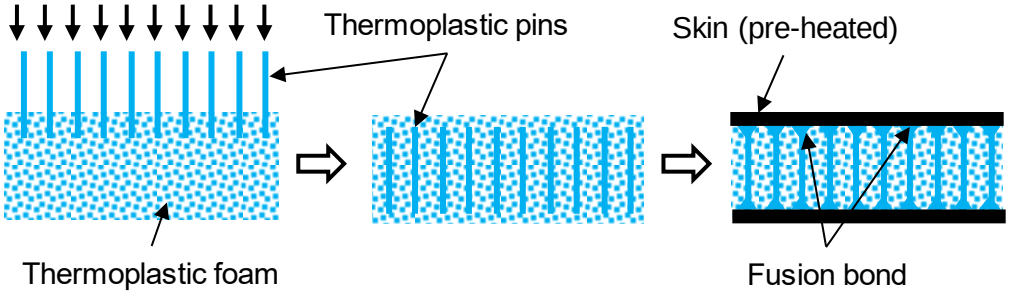


Figure 93: Schematic illustration of TPC foam reinforcement concept 1

8.2.3 Concept 2

Another concept is developed that takes the principle of riveting as an example. Similar to the initial concept, thermoplastic pins of a length higher than the core's thickness are introduced into the core. Prior to fusion bonding the skins to the core, a hot stamp device melts the ends of the pins and forms a kind of rivet head, which is simultaneously fusion bonded to the foam core, see Figure 94. Finally, the thermoplastic composite skins are heated separately, placed onto the core and fusion bonded to the reinforced core.

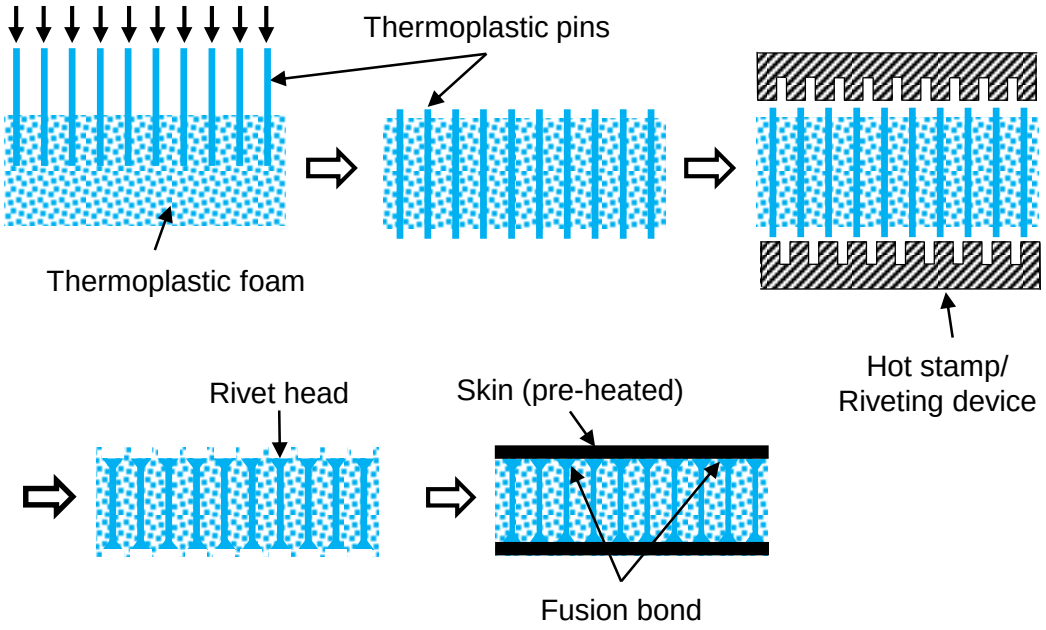


Figure 94: Schematic illustration of TPC foam reinforcement concept 2

8.3 MATERIALS

The skin material consists of two PEEK pre-impregnated carbon fibre reinforced fabric plies (±45°/0°,90°), combined with two UD plies (+45°,-45°) and a PEI film having a thickness of 125 µm. The skins are consolidated at 375 °C under a pressure of 1 MPa. As core structure, the PEI Airex® R82.60 foam with a density of 60 kg/m³ and 19 mm thickness provided by Gaugler and Lutz oHG, Germany is used.

Two different pin types are investigated in this study. Besides PEI pins, pins with continuous carbon fibres reinforced PEI (FVC: ~32 %) referred to as CF pins are used. The pins have a rectangular cross-sectional area of 1.6 mm x 1.6 mm, various lengths (17 mm, 26 mm and 33 mm), and are introduced into the foam with 1 pin/100 mm² in a quadratic pattern. The carbon fibres in the CF pins are orientated in the pins' longitudinal direction.

8.4 EXPERIMENTAL

8.4.1 Specimen preparation

In this study the two different foam modification concepts are investigated with different pin configurations, see Table 24. To improve the compression strength, the pins are introduced orthogonally (90°) to the skins. As proposed by other researchers [197] a pin angle of 45° seems advantageous for improving the shear strength, nevertheless sandwiches with pure 90° PEI pins are also investigated. Depending on the concept and the angle, the pin lengths vary, see Table 24. Specimen designation is explained as follows:

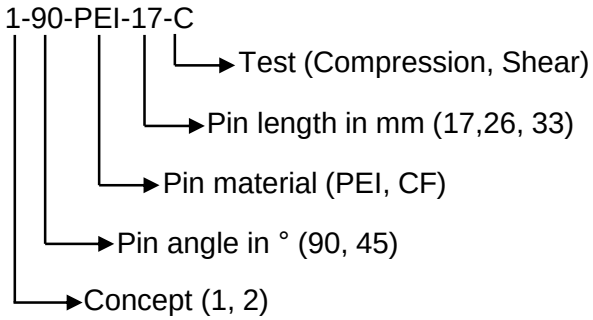
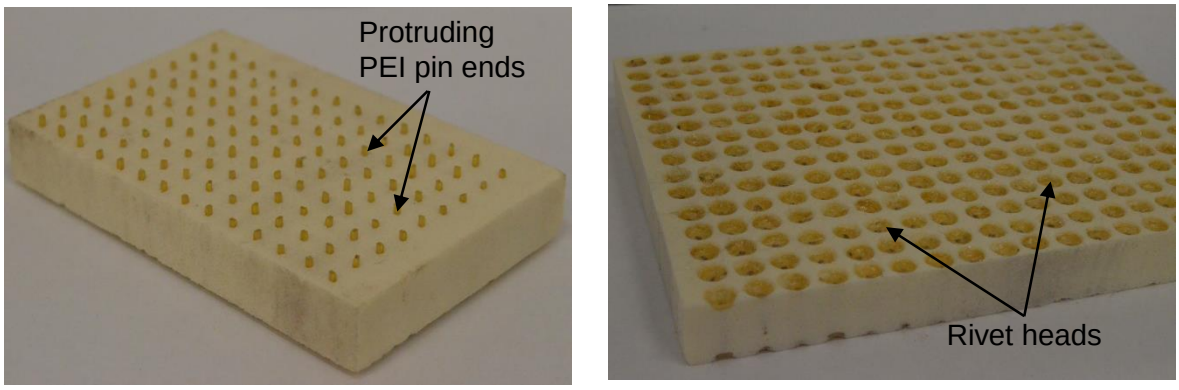


Figure 95: Specimen designation

Table 24: Test matrix for foam modification

Concept	Angle [°]	Pin	Pin length [mm]	Compression	Shear
1	90	PEI	17	1-90-PEI-17-C	1-90-PEI-17-SH
		CF	17	1-90-PEI-17-C	-
	45	PEI	26	-	1-45-PEI-26-SH
		CF	26	-	1-45-CF-26-SH
2	90	PEI	26	2-90-PEI-26-C	2-90-PEI-26-SH
		CF	26	2-90-CF-26-C	-
	45	PEI	33	-	2-45-PEI-33-SH
		CF	33	-	2-45-CF-33-SH

Exemplarily, foams with pins introduced according to concept 2 are displayed in Figure 96.



a) **b)**

Figure 96: Foam with integrated pins according to TPC foam reinforcement concept 2: a) before riveting and b) after riveting

According to the test matrix in Table 24, sandwich specimens are manufactured with dimensions of 150 by 200 mm, which supply five specimens for compression and three specimens for shear testing. To preclude periphery effects, the sandwiches are trimmed at each side. Sandwiches are manufactured with a skin temperature of 320 °C, a pressure of 0.2 MPa and a compaction distance of 2 mm. An increase to 320 °C skin temperature in comparison to the recommended temperature of 300 °C (chapter 6.4) is selected since it is assumed that a larger amount of heat energy is advantageous to softening the pins.

8.4.2 Test setup

For the characterisation of the modified sandwiches, compression testing in flatwise plane is conducted according to DIN 53291 and shear tests in accordance with DIN 53294 are performed. Specimen preparation for testing is conducted as described in chapter 6.2.2. Failure modes of the sandwich specimens are again evaluated based on the evaluation based on DIN EN ISO 10365.

8.5 RESULTS

Figure 97 displays the normalised compression strength (normalised to the unmodified sandwich compression strength) of the reinforced foam core sandwiches in comparison to the compression strength of an unmodified sandwich. The reinforcement of the foams according to both concepts leads to a significant increase in compression strength. In the case that the foam is strengthened with PEI pins an increase in the compression strength by factor 4 can be achieved. Due to the high stiffness of the carbon reinforced pins, the compression strength can be improved approximately by a factor of 6 with the application of CF pins according to concept 1 and by up to a factor of 10 according to concept 2.

Figure 98 shows the normalised shear strength results (normalised to the shear strength of unreinforced sandwiches), which vary considerably. In the case of the foam core being modified with 90° PEI pins, the shear strength cannot be improved or is even reduced. Under shear loads, the pins introduced according to concept 1 fail at the joint between pins and skins, which hinders an improvement of the shear performance.

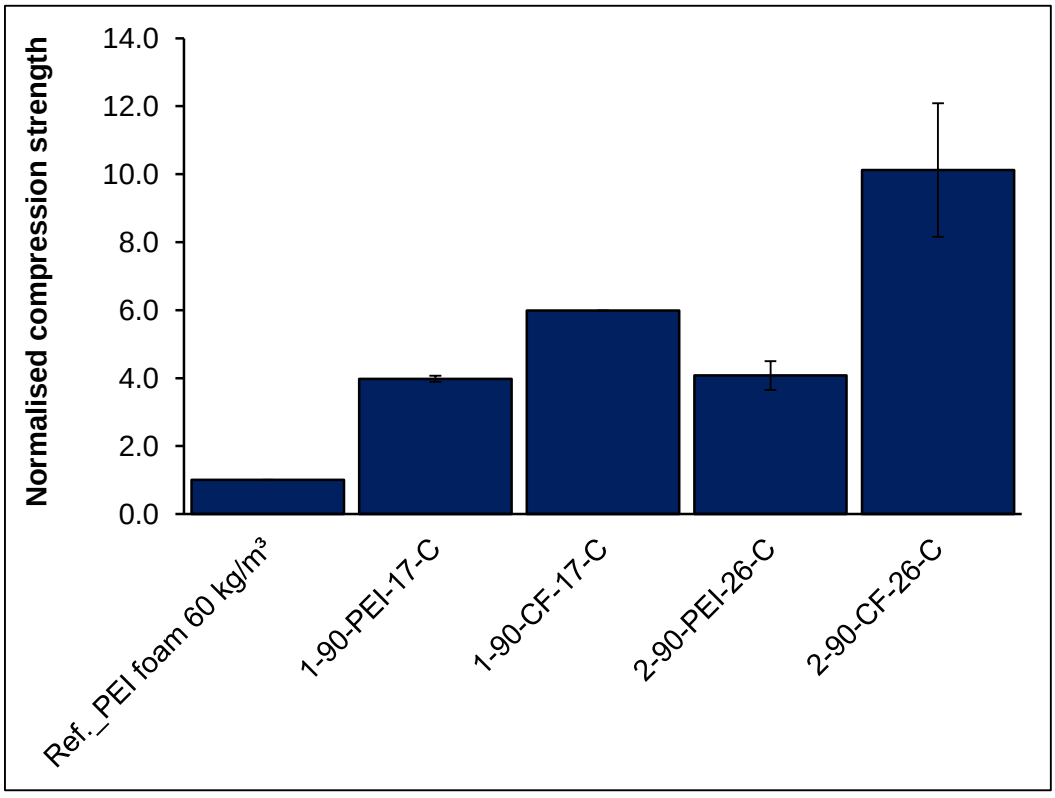


Figure 97: Foam modification - compression strength results

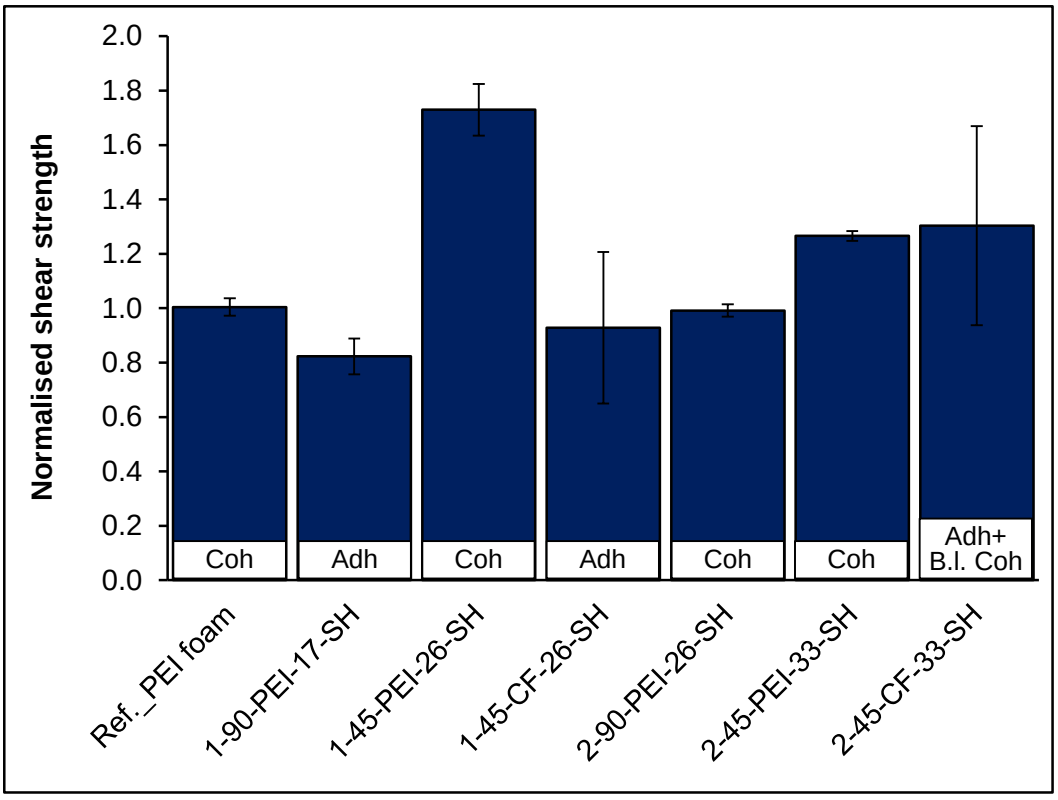


Figure 98: Foam modification - shear strength results

In addition, the presence of the pins reduces the bonding area between skins and core, and thereby the bonding quality with the result that the sandwich specimens fail adhesively within the interface. In comparison, unmodified specimens (Designation: Ref._PEI foam) fail cohesively within the core structure, see Figure 99.

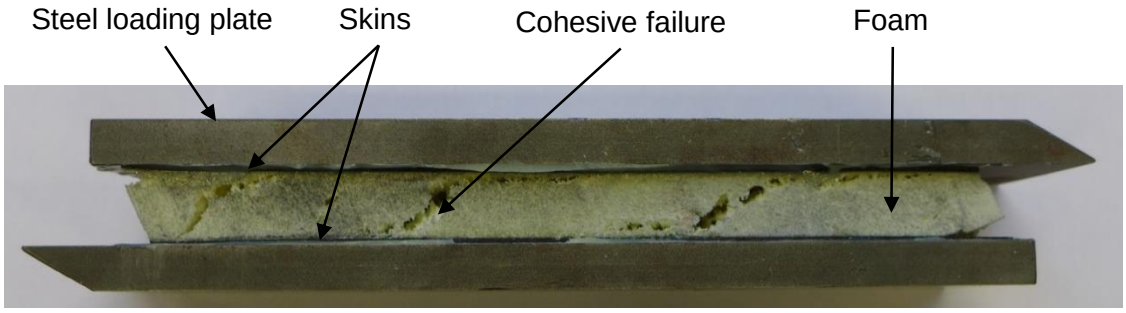


Figure 99: Cohesive failure of unmodified specimen (Ref._PEI foam)

In the case of the foam being modified with 90° PEI pins according to concept 2, the shear strength in combination with cohesive failure is comparable to the unmodified specimens. The pins do not seem to have much influence on the performance, however the bond strength by riveting is improved compared to concept 1.

Strengthening of the core with 45° pins leads to a significant improvement of the shear strength in most cases. The best result is achieved by strengthening the foam core according to concept 1 with PEI pins with an improvement in shear strength by a factor of 1.72. However, the modification with CF rods according to concept 1 does not improve the shear performance.

Due to the carbon fibre reinforcement of the pins (FVC = ~32 %), a lower amount of PEI is available to create a fusion bond to the skins, which is confirmed by the failure mode where all specimens failed adhesively within the interface, see Figure 100. Therefore, the shear strength of the specimens is lowered.

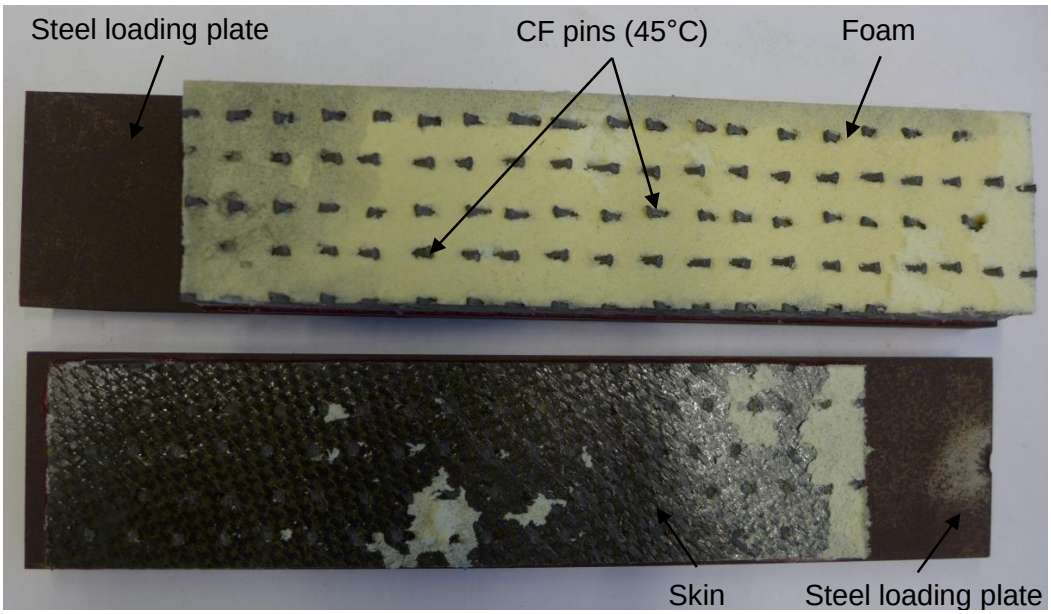


Figure 100: Specimen 1-45-CF-26-SH: Adhesive failure within the interface

In the case of the specimens being modified according to concept 2, the shear performance is slightly improved (~ factor 1.3). Due to the riveting process, the bonding quality is improved with both pin types. However, only by the application of pure PEI pins the bond can withstand the shear loads. The application of CF pins still weakens the fusion bond due to the low quantity of PEI material in the pins. A mix of adhesive and boundary layer cohesive failure occurs. As the pins strengthen the foam and avoid failure of the core, the shear loads are transferred into the interface, causing it to fail and leaving the reinforced core intact, see Figure 101.

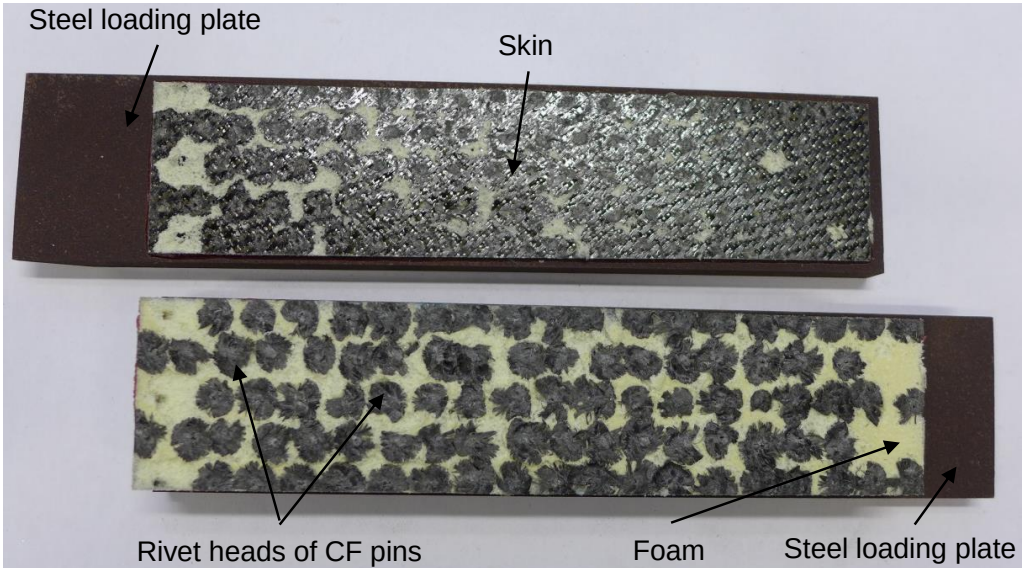


Figure 101: 2-45-CF-33-SH: Adhesive and boundary layer cohesive failure

8.6 DISCUSSION

The previously presented results have to be evaluated carefully. By introducing either PEI or CF pins into the core, its weight and its density is increased. The increase of weight is strongly dependent on the pin length, which varies with pin introduction angle and utilised pin type. In Figure 102 the density and the factor of the density increase compared to unmodified foams is given. Depending on the pin length, the density is increased by a factor of 1.5 - 1.9. A modification with 90° pins leads to a density increase by a factor of ~1.5 – 1.75, 45° pins increase the density in most cases by a factor of > 1.7. Where pins are applied at 45° according to concept 2, the density of the foam is almost doubled. At this point it should be mentioned that no pinning weight optimisation effort was undertaken within the framework of this project. As a result, there is significant room for improvement.

Figure 103 and Figure 104 show the compression strength and the shear strength related to the core density. In order to evaluate the efficiency of the foam modification, the specific strengths are compared to a PEI foam with a density of 110 kg/m³ (Ref._PEI foam 110 kg/m³), which approximately corresponds with the densities of the modified foam cores. Moreover, the results are compared to the performance-to-density ratio of a honeycomb based sandwich (Ref._Honeycomb).

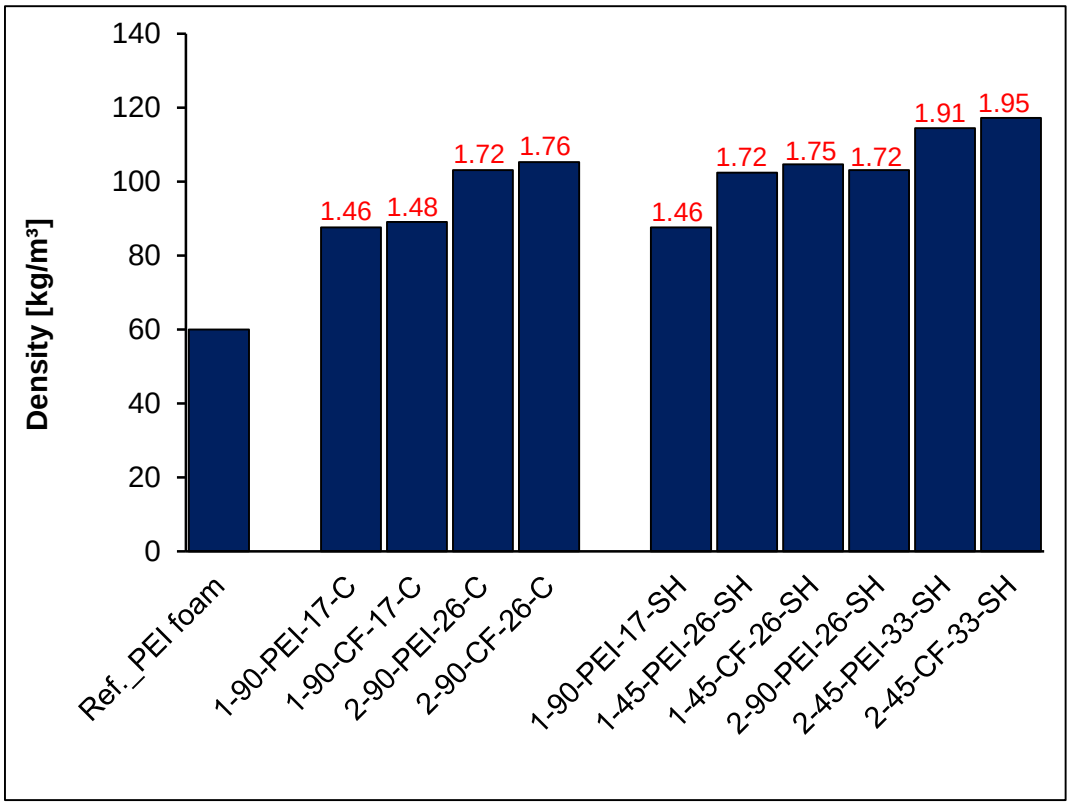


Figure 102: Density of foams (unmodified and reinforced)

By modifying the foam cores, the specific compression strength can be significantly improved even with an increased foam density. A PEI foam with a density of 110 kg/m³ features an equal specific compression strength to a foam of 60 kg/m³. This shows that the modification of the

foam is more efficient than the application of foam of higher density. Additionally, the specific compression strength of the modified foam core sandwiches is even equal or higher than that of honeycomb sandwiches. The specific shear performance results show that an improvement could not be achieved. The shear strength in total can be improved, though the increased density caused by the pins leads to a decline in the specific shear strength in most cases. Only the specific shear strength of the specimen modified with 45° PEI pins according to concept 1 shows the same specific shear strength as unmodified 60 kg/m³ and 110 kg/m³ foam cores.

Nonetheless, the investigations show that for CF pins the weakest link is no longer the core, but the interface. Therefore, in order to take full advantage of the core reinforcement with CF pins further research is needed to improve the bond between skins, core and pins, as well as to reduce the weight increase e.g. by applying different pinning patterns, rod cross section, etc.

Furthermore, a promising solution could be local reinforcement of the foam in heavily loaded areas where higher compression and shear properties are required. This enables a widening of foam sandwich applications. Therefore, this work shows high potential for the application of TPC sandwiches with customised, modified foam cores.

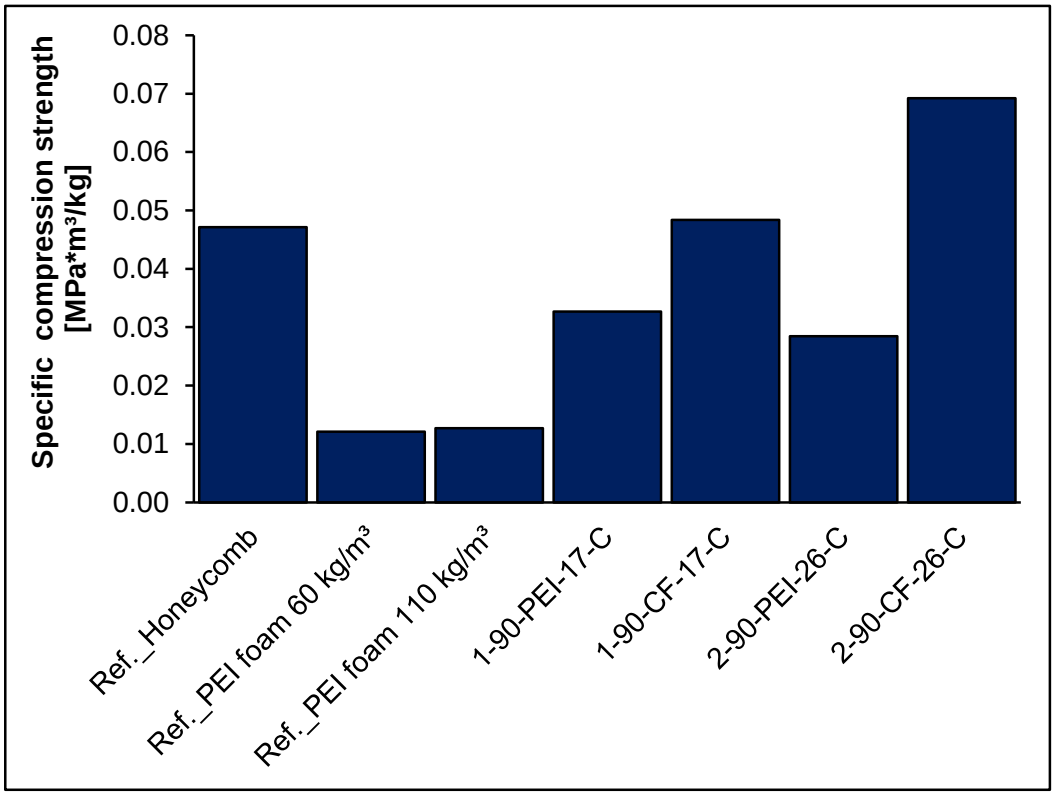


Figure 103: Compression strength related to the core density

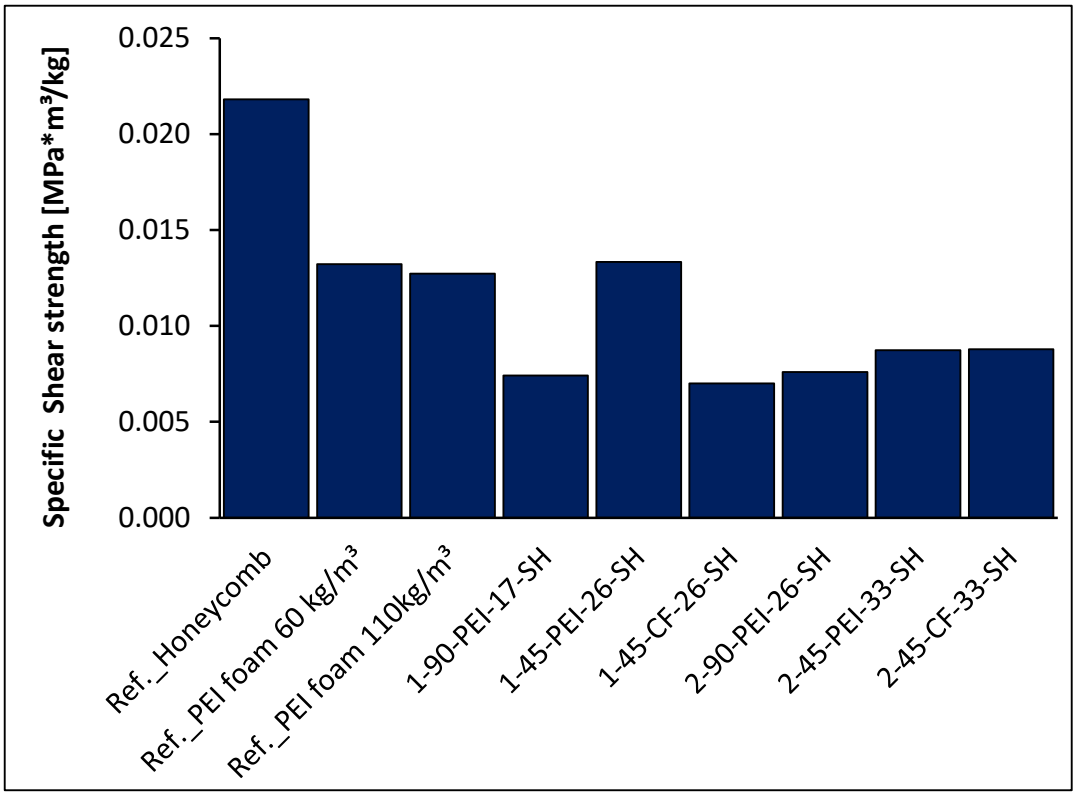


Figure 104: Shear strength related to the core density

9. SHAPED SANDWICHES

In the previous chapters, investigations into the manufacturing of flat, two-dimensional (2D) panels are presented. In order for the technology to be further pursued in the future, it is required to show the possibility of manufacturing shaped sandwich panels. Therefore, this chapter aims to show the feasibility of producing shaped carbon fibre reinforced Polyetheretherketone skin and Polyetherimide foam core (CF/PEEK-PEI) based sandwiches. The feasibility shall be proven by realisation of the shaped shear panel, which has been derived from helicopter applications and has been defined as the target structure for this study, see Figure 105.

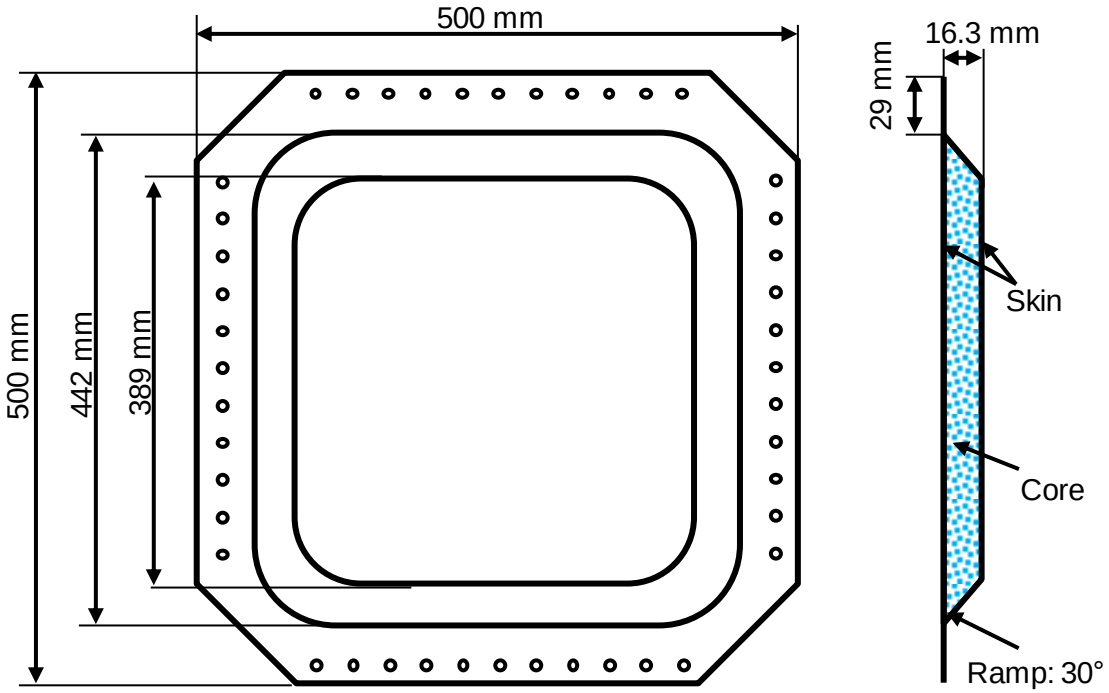


Figure 105: Shaped shear panel

Firstly, possible manufacturing approaches are presented, followed by investigations into the process window for the realisation of shaped sandwiches. Here, the process window includes the investigations on the skin-to-core bond as derived in chapter 5 and 6. Thirdly, according to the process window, the feasibility of the approaches is evaluated. Finally, the most suitable approach is selected for the realisation of the shear panel.

9.1 MANUFACTURING APPROACHES

In public literature two different approaches based on compression moulding have been proposed to realise shaped thermoplastic sandwiches, see chapter 2.5.

1. Direct forming and joining of skins and core
2. Thermoforming of 2D sandwiches into shaped structures

A third trivial approach is supplemented by the author:

3. Forming of skins and core prior to joining

These approaches will be explained in more detail below.

The most cost-effective way to realise a shaped sandwich panel is manufacturing in one step [69]. Foam and skins are simultaneously formed and fusion bonded. In doing so, the change of the core density needs to be considered, since the core is differently locally compacted. The approach is illustrated in Figure 106.

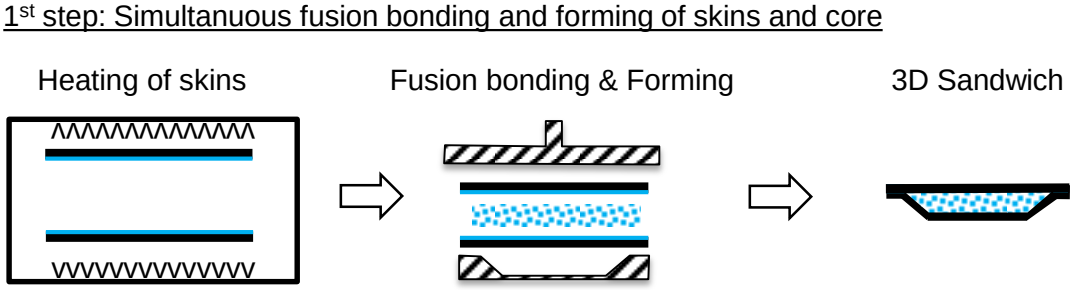


Figure 106: Approach 1 - Direct forming and joining of skins and core

Different technologies exist in order to form a flat sandwich panel into a shaped structure, see chapter 2.5.2. This means that first a flat sandwich panel is produced by fusion bonding, which is formed in a following step. For this approach, the local core compaction needs to be examined as well. This approach is illustrated in Figure 107.

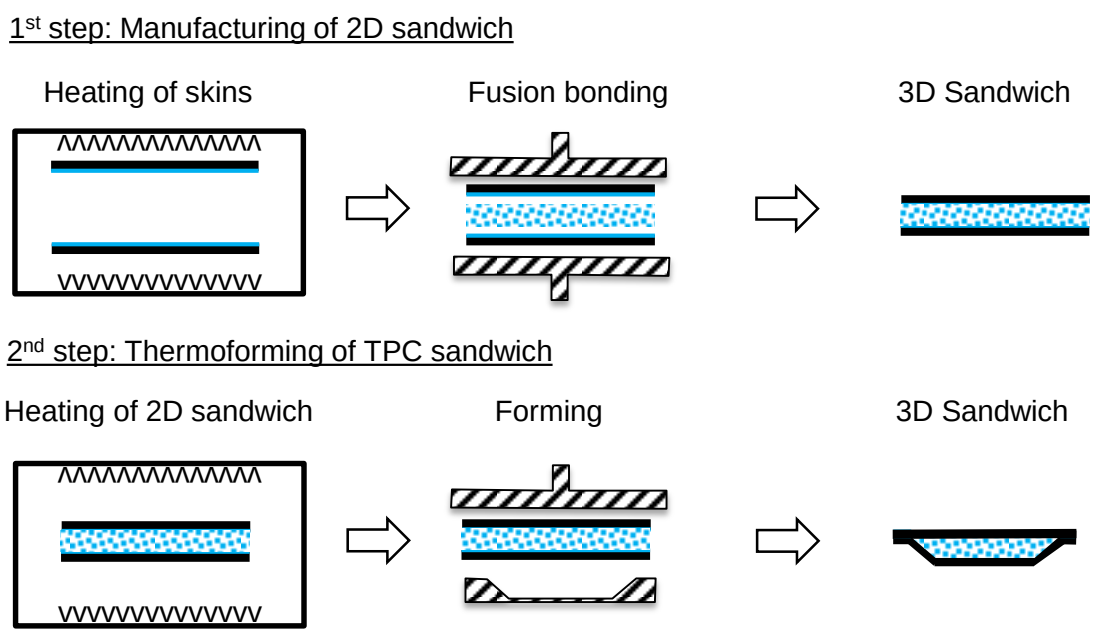


Figure 107: Approach 2 - Thermoforming of flat sandwich structures into shaped structures

A third, more trivial, method to realise the shaped sandwich panel is to form skins and core separately before joining. It is assumed that this approach is relatively simple compared to the other approaches since the process window for forming and bonding are decoupled. Furthermore, by prior shaping the core, local core densification can be avoided. Nevertheless, this approach will have a negative impact on the cycle time due to the need of three separate manufacturing steps. The approach is visualised in Figure 108.

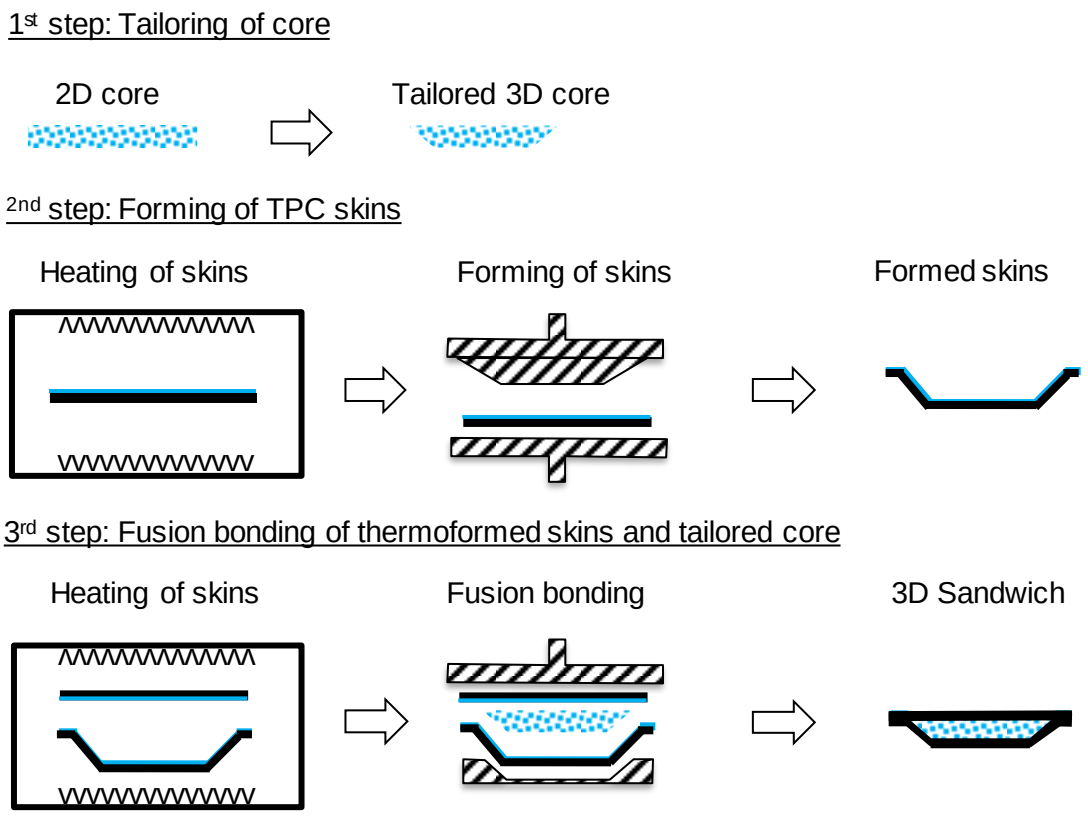


Figure 108: Approach 3 - Forming of skins and core prior to joining

A possibility to shorten the manufacturing effort of approach 3 “Forming of skins and core prior to joining” could be to leave out the tailoring step of the core. The core is then compacted during the process of joining with the formed skins, which will lead again to high foam core densification in the ramp zones.

9.2 PROCESS WINDOW

The investigations in the previous chapters show that the process window to enable a strong bond between CF/PEEK skins and a PEI core is narrow due to the different process conditions required for the two dissimilar materials. Skin- to-core joining can only be realised by enriching the CF/PEEK skins with a PEI film. According to Aström et al. [22] the realisation of a shaped panel increases the demand concerning the process window since more process requirements for forming the skins and the core will be added. Phenomena such as skin de-consolidation, foam collapse or foam tearing as well as a weak bond have to be avoided in order to achieve a sandwich of sufficient quality [22,71,73]. To control these phenomena, temperature and pressure limits must be determined for each sandwich constituent in order to find out if they can be fitted in one global process window that additionally meets the requirements of fusion bonding.

9.2.1 Process window: core

Forming of the core is limited on the one hand by core compression due to high pressure and temperature, or core collapse due to extensive heating, and on the other hand by foam tearing

due to limited formability of the foam in the case that the foam is insufficiently heated [71]. Figure 109 presents the compression strength of the Airex® PEI foams with different densities dependent on temperature, where it becomes clear that the compression strength is highly dependent on the temperature and it decreases around 50 % when the foams are heated to 160 °C. Further experimental trials show that the core collapses without loading at a temperature around the T_g of PEI.

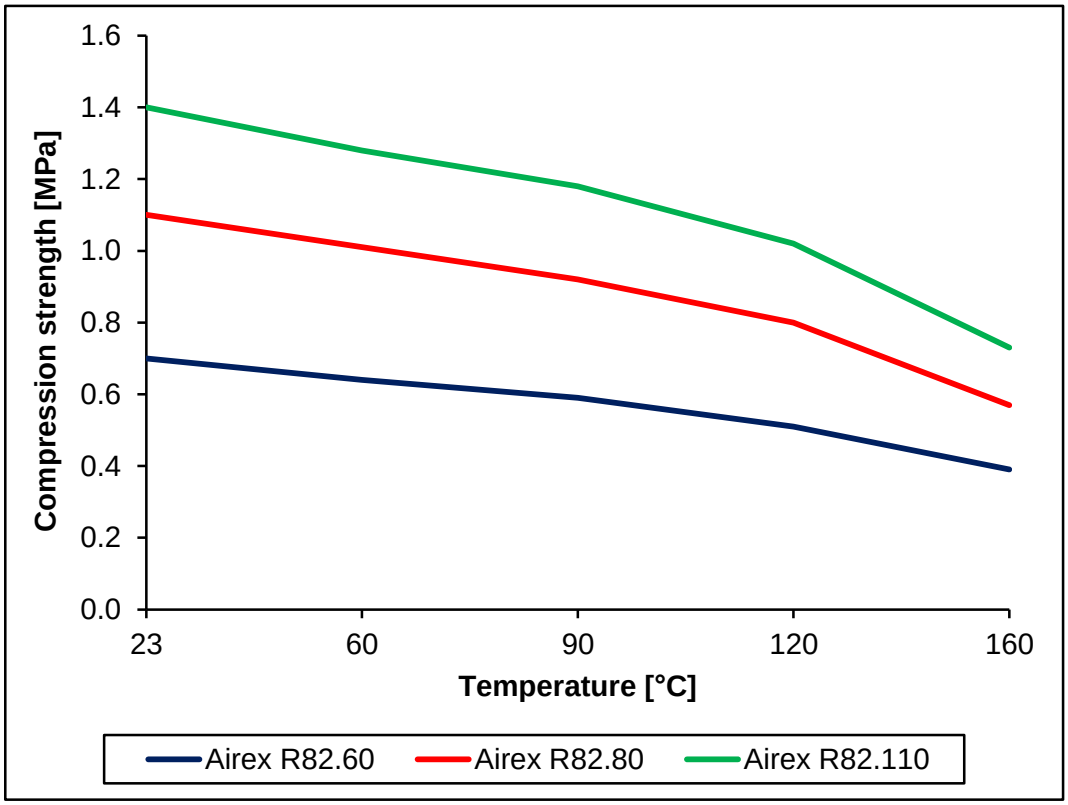


Figure 109: Compression strength of PEI foams depending on the temperature

Rozant et al. [71] showed by tensile testing of PEI foams with a density of 80 kg/m³ under elevated temperatures, that a temperature range of 165 °C – 185 °C is required to avoid foam tearing under strain. Furthermore, it was shown that the forming strain has to be below 20 % to avoid cell damage.

Combining the compression strength results and the proposed forming temperatures, a forming process window is determined which is limited by 165 °C as the minimum temperature and 185 °C as the maximum temperature, while the pressure should not exceed 0.39 MPa - 0.74 MPa depending on the foam density to avoid extensive core compaction. The lower limit of the pressure is not investigated.

9.2.2 Process window : skins

Forming of the skins requires heat to soften the polymer and pressure to form the laminate into the aimed shape. The limiting phenomena are on the one hand skin de-consolidation and polymer degradation while on the other a high rigidity of the material restricts the forming process [71]. Forming of continuous fibre reinforced polymer materials is primarily controlled by forming the fibre reinforcement structure [198]. This is opposed to forming of pure

thermoplastic materials which can be sheared and stretched during the forming process [198]. The fibre reinforcement restricts any major elongation or compression since the fibres can neither lengthen nor shorten [199]. Due to the stiffness of fibres, breaking occurs when lengthening the fibres, while kinking and breaking occurs when shortening the fibres [199]. The deformation of continuous fibre reinforced laminates is described in theory by interply and intraply slipping or by a combination of both [198]. Interply slipping is referred to as the relative movement of adjacent fibre plies. Intraply slipping refers to phenomena such as intraply shear, straightening of the fibres, elongation of the fibres and transverse flow of the fibres [198]. Intraply slipping is highly dependent on the architecture of the fibre reinforcement.

Forming of flat laminates into 3D formations is governed by a complex combination of interply and intraply slipping, which requires a detailed investigation of different processing parameters as well as a detailed study about the drapeabilty of the fibre reinforcement structure. However, by simplifying the 3D deformation into a 2D deformation such as forming a right angle bend or similar, the forming behaviour can be reduced to the interply slipping phenomenon [199]. Due to the restricted lengthening of fibres plies, forming causes interply shearing as a consequence of pressure and velocity gradient through the thickness of plies and acts on the polymer matrix which is located between the single fibre plies. It is now assumed that the polymer matrix is softened or molten during forming. Due to the nature of softened polymers, the material offers an internal resistance against shearing, which means that a specific amount of shear force is necessary for the deformation of the polymer material [183]. In the case that the shear stress acting on the plies does not exceed the yield shear stress of the matrix material, interply slipping cannot take place and the shear forces act on the fibre reinforcement structure itself. This may finally result in buckling of the fibres at the inside of the bend (inner radius), or in fibre breakage events at the outside of the bend region (outer radius) [199]. In order to avoid fibre damage, the shear force has to exceed the yield shear stress of the matrix. The yield shear stress can be brought in relationship with the shear viscosity η of polymers and the shear velocity $\dot{\gamma}$ [183] in form of

$$\eta = \frac{\tau}{\dot{\gamma}} \qquad \textbf{Equation 25}$$

In general, the viscosity highly depends on the shear velocity, the temperature and on several polymer characteristics such as molecular weight [183]. However, for low shear velocities of polymers the shear velocity can be neglected. In this case polymer melting can be treated as a Newtonian fluid [183]. As a result, the yield stress of the matrix polymer is dependent on the viscosity which is a function of the temperature for low shear viscosities. These assumptions are considered for the case of CF/PEEK skin forming.

In order to determine the limit conditions, in particular the minimal required temperature for forming the CF/PEEK laminates, experimental forming trials are conducted. Under isothermal conditions, consolidated CF/PEEK laminates consisting of three plies (4HS, 220 g/m², (±45°; 0°,90°;±45°) are formed at different temperatures around the melting temperature of PEEK into a steel mould having an omega profile shape, see Figure 110. Two different kinds of pressure levels were used, in particular 0.2 MPa (the lowest possible pressure of facilities) and 1 MPa, the pressure used for consolidation of CF/PEEK skins. The process is conducted isothermally, meaning that mould and laminates are both heated to 335 °C, 340 °C, 345 °C and 350 °C.

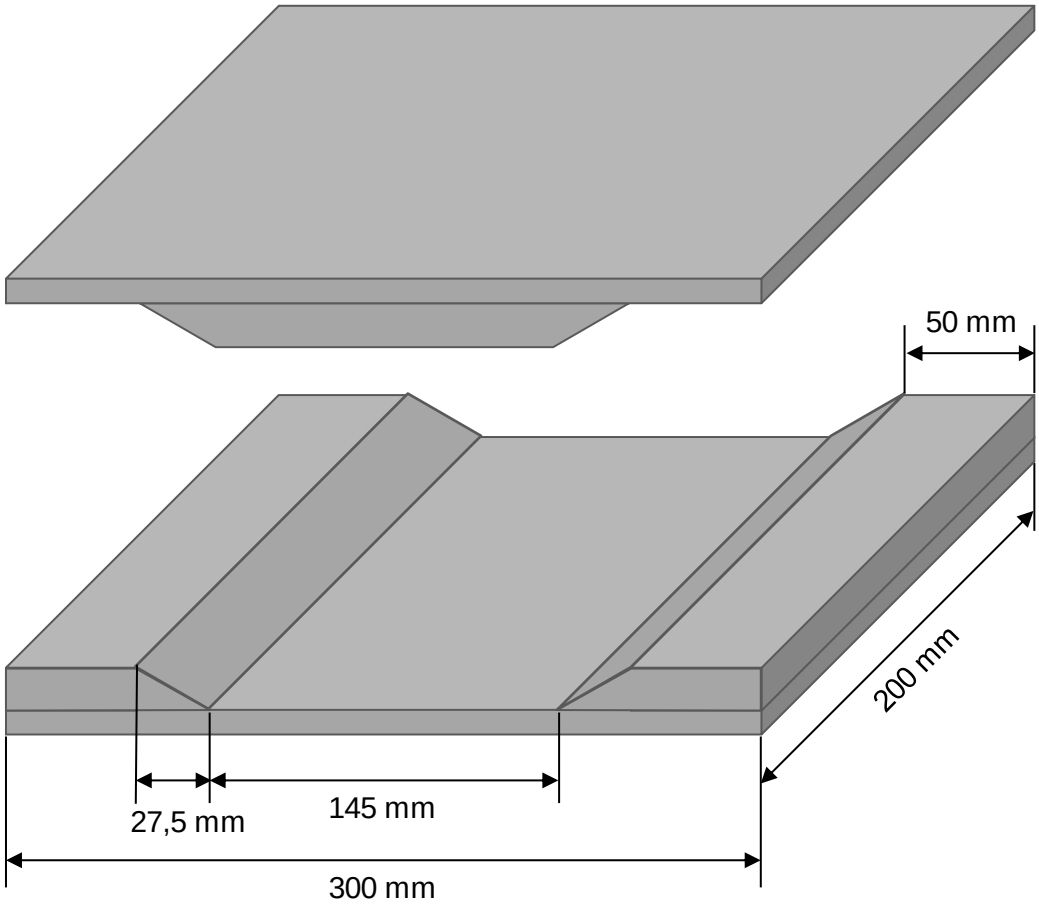
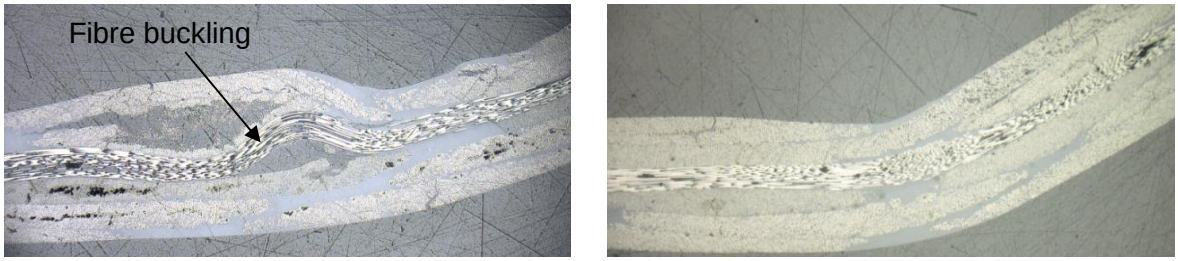


Figure 110: Shape of the mould for skin forming trials

The investigations reveal that the skins cannot be formed properly at temperatures below the melting point of PEEK under isothermal conditions. Although all temperatures in combination with both pressure levels enable forming into the defined shape, microscopic pictures show that temperatures below T_m of PEEK do not enable enough interply slipping, resulting in fibre buckling at the inside of the bend, see Figure 111a. Temperatures (~350 °C) above T_m seem to enable interply slipping and the laminate can be formed without fibre buckling, see Figure 111b. Furthermore, the experimental trials reveal that a higher pressure of 1 MPa does not improve the forming quality at these temperatures.

Following the isothermal trials, non-isothermal forming trials are conducted. The laminates are pre-heated in an oven and placed into a cold mould and formed. Since heat loss during transfer needs to be considered, the laminates must be heated far above 350 °C, which is determined to be the minimum forming temperature under isothermal conditions. However, during heating the de-consolidation phenomenon is faced again, see chapter 5.1.



a) **b)**

Figure 111: Fibre buckling at a forming temperature of 335 °C and a pressure of 0.2 MPa, b) Proper forming at a forming temperature of 350 °C and a pressure of 0.2 MPa

Furthermore, the trials show that the laminate is cooled so rapidly when touching the cold mould, that re-consolidation at exemplarily a skin pre-heat temperature of 390 °C is restricted, see Figure 112a. Pre-heat temperatures above 405 °C and pressure of 1 MPa are required to re-consolidate the laminates successfully, see Figure 112b.

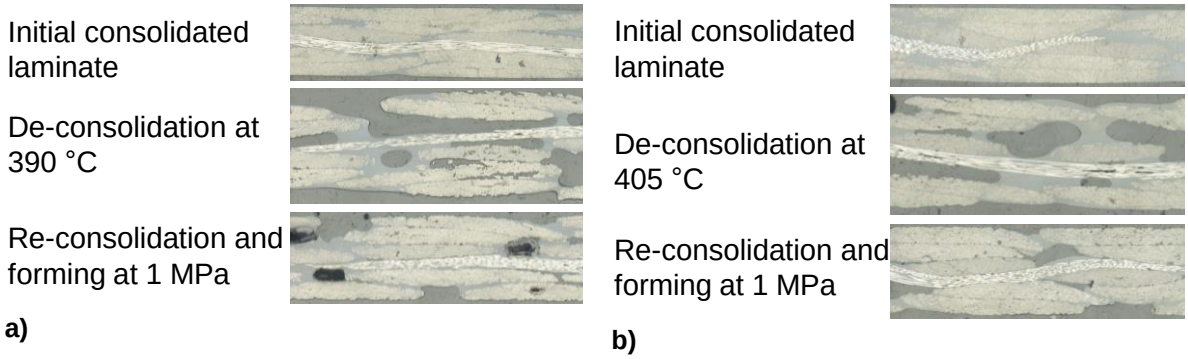


Figure 112: Re-consolidation at a) 390 °C and b) 405 °C

In conclusion, the CF/PEEK can be thermoformed under isothermal conditions at temperatures of around 350 °C and a low pressure of 0.2 MPa. Non-isothermal processing requires significantly higher temperatures of more than 405 °C and a pressure of 1 MPa.

9.2.3 Process window: sandwich

Figure 113 illustrates the different processing windows for the forming of skins under isothermal and non-isothermal conditions, foam forming and fusion bonding. For skin and foam processing the limiting phenomena are also presented. For fusion bonding the limiting phenomena such as skin de-consolidation, core collapse and weak bonding are not illustrated in the figure, since they are described in detail in the previous chapters of this study. Figure 113 visualises clearly the temperature and pressure gap for non-isothermal conditions for forming skins and foam core. Furthermore, the narrow process window for fusion bonding is emphasised.

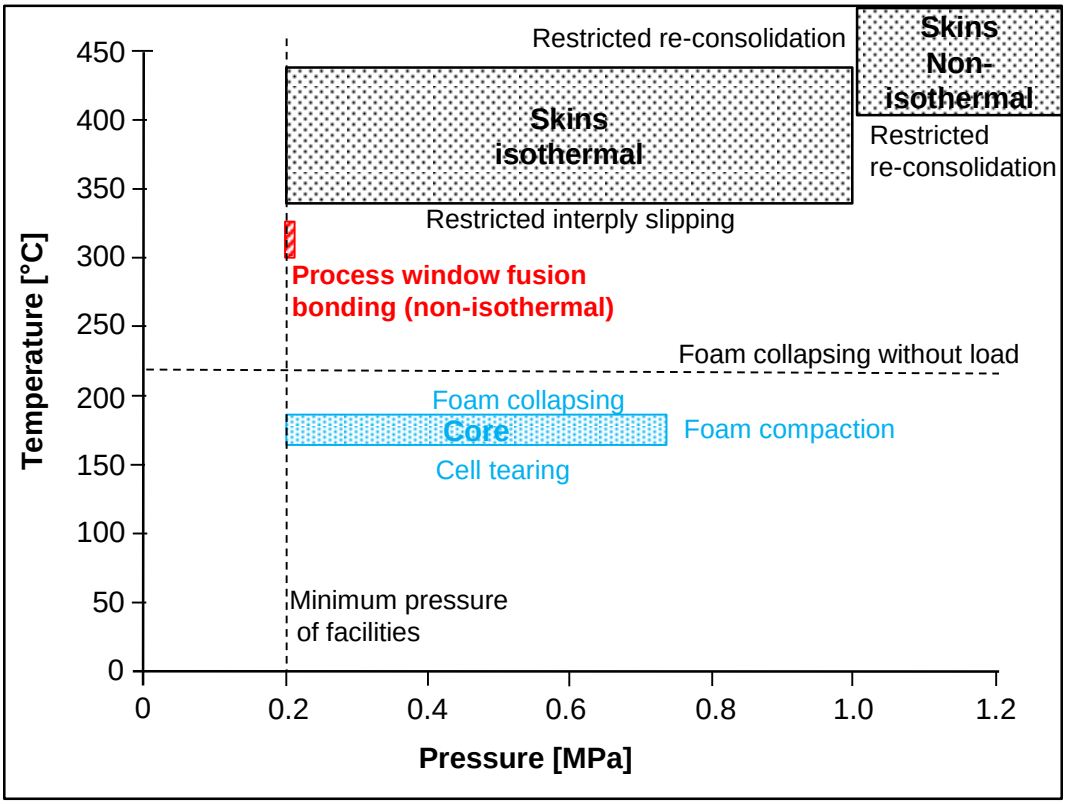


Figure 113: Overview of processing windows for forming skins and core as well as fusion bonding skins and core

In the following sections, it is evaluated if the proposed manufacturing approaches enable the strict observance of the different processing windows in order to realise a shaped sandwich panel.

9.3 EVALUATION OF MANUFACTRUING APPROACHES

In consideration of the process windows illustrated in Figure 113, it becomes clear that skins and core cannot be formed and fusion bonded in one step. Under non-isothermal conditions the skin temperature to enable a strong skin-to-core fusion bond core is determined to be 300 °C – 320 °C with 320 °C – 340 °C as the equivalent pre-heat temperatures, where by the upper temperatures already led to slight core collapse. At higher temperatures, required for forming the skins in order to allow interply slipping, the CF/PEEK skins de-consolidate due to the release of internal stress. To re-consolidate the laminates, temperatures above 405 °C are needed and a pressure of at least 1 MPa is required. Regardless, re-consolidation on the foam is not feasible since the core cannot withstand these conditions. At the elevated temperatures, additionally needed for forming of the core, the compression strength significantly decreases below 0.5 MPa resulting in extensive core compaction under higher loads.

Approach 2 “Thermoforming of 2D sandwiches into shaped structures” requires for the first step fusion bonding of flat skins and a flat core, which is readily possible as proved in the preceding chapters. In the following step, the flat sandwich panel has to be pre-heated to allow forming. According to the determined process window (Figure 113), different pre-heat conditions for skin and core have to be realised to allow forming while avoiding core collapse

or core compaction and fibre buckling. Figure 114 illustrates schematically the temperature gap between skin forming temperature and core forming temperature. Furthermore, pressure during heating should be applied on the skins in order to avoid skin de-consolidation.

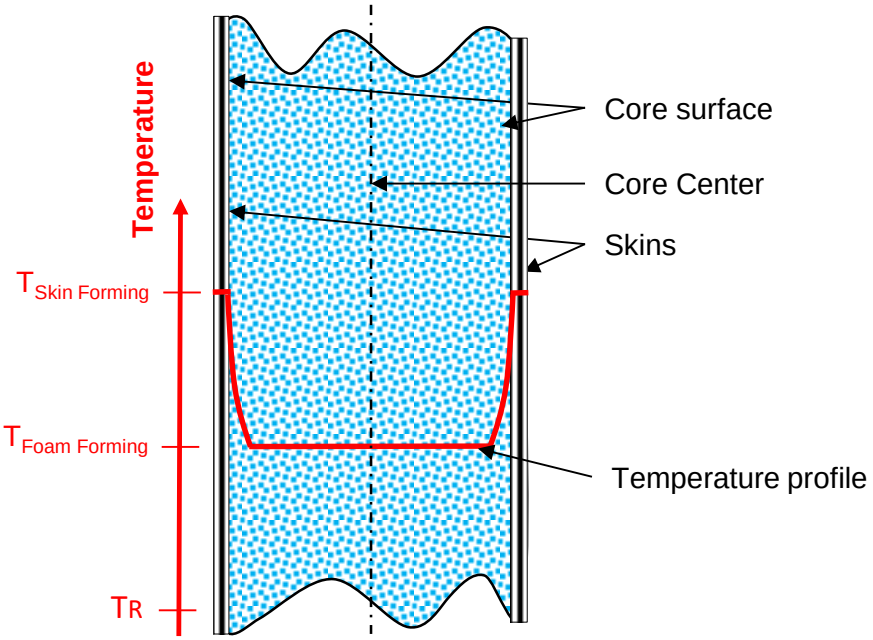


Figure 114: Temperature gap for forming skins and core according to the manufacturing approach 2

Rozant et al. [71,73] developed a two-stage heating method in order to realise a temperature gradient through the whole sandwich, which allows the forming of fibre reinforced PEI skins and a PEI foam core. The whole sandwich is first pre-heated to a basic temperature level, followed by a preferentially fast heating of the skins. Fast heating reduces the amount of heat transfer into the core centre. However, in the case of the application of CF/PEEK skins and a PEI foam, the temperature gap for skins and core is much wider than for all-PEI sandwiches. Therefore, it seems that a high amount of heat being transferred into the core cannot be avoided and it seems impossible to prevent core collapse or compression during the forming step.

A possible solution to realise a shaped sandwich consisting of CF/PEEK skins and PEI foam lies in the separation of forming each sandwich constituent individually as well as the decoupling of forming and fusion bonding. The constituents can be formed according to the determined process windows (Figure 113) and fusion bonded in a following step according to the manufacturing process described in the preceding chapters of this study.

In the following section, investigations on the realisation of the shaped sandwich panel according to the manufacturing approach 3 ”Forming of skins and core prior to joining” are presented. Firstly, investigations on a simplified shaped sandwich are conducted before the shear panel is realised.

9.4 MATERIALS

The skin material consists of two pre-impregnated carbon fibre reinforced PEEK fabric plies (±45°/0°,90°) combined with two PEEK pre-impregnated carbon fibre reinforced unidirectional (UD) layers (+45°/-45°). The fibre volume fraction of the consolidated laminate is approximately 60 %. The skins are superficially enriched on one side with Ultem®1000 (Solvay, USA) PEI films with a thickness of 125 µm while simultaneously forming and consolidating in a shaped tool at 375 °C and 1 MPa, see Figure 115. The hybrid skin setup consisting of fabrics and unidirectional layers is selected due to the fact that the UD layers avoid extensive diffusion of the PEI polymer into the laminate during consolidation, see chapter 5.3. Consolidation and forming of the skins for the shear panel are performed in the same way.

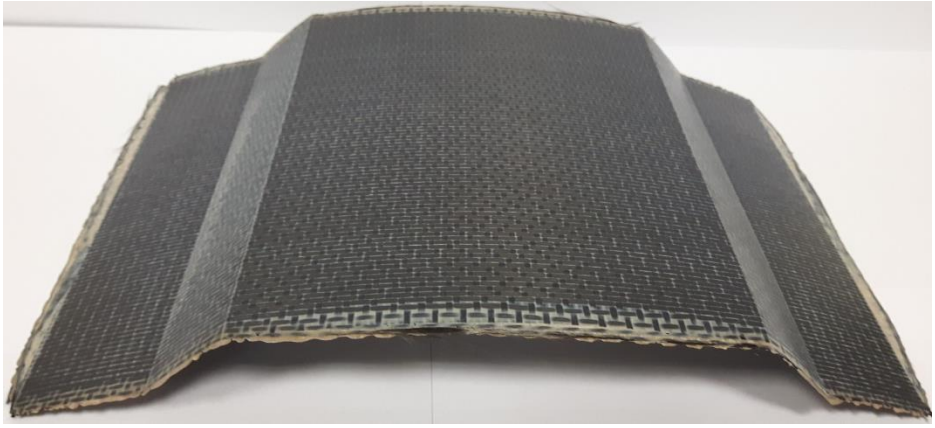
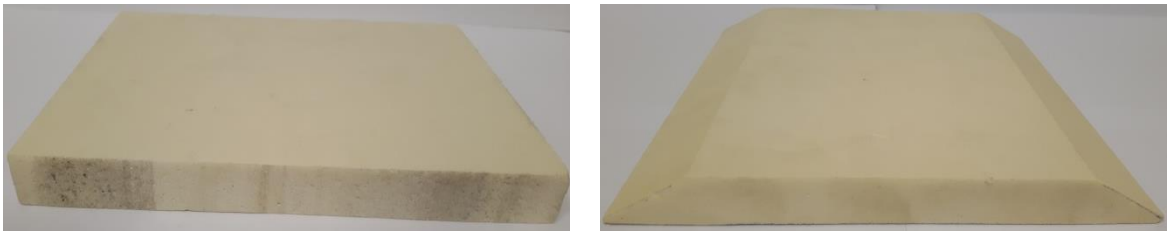


Figure 115: Consolidated and formed skin

As core structure, PEI Airex® R82.60 foam with a density of 60 kg/m³ and a thickness of 19 mm provided by Gaugler and Lutz oHG, Germany is used.

In order to investigate if the core has to be formed separately or if the core can be formed, in particular compacted at the side ramps by the heated skins, two different core shapes, namely an ‘as-is’ foam core and a customised foam core, are prepared for the joining trials, see Figure 116. The customised (by machining) core has an excess of 2 mm in each direction to enable a compaction distance of 2 mm, which allows even core compaction in the boundary layer.



a) **b)**

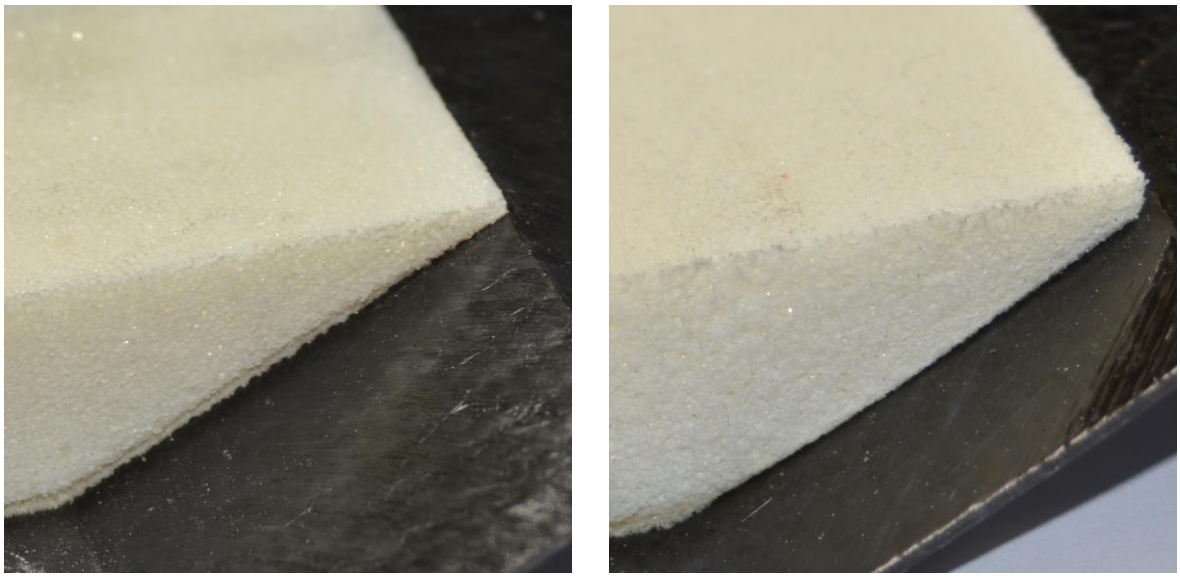
Figure 116: a) ‘As-is’ foam and b) Customised foam

9.5 EXPERIMENTAL

9.5.1 Specimens preparation

According to the developed non-isothermal compression moulding process (chapter 5), the shaped sandwich panels are manufactured. The skins as well as the shaped transfer plate are heated to 320 °C (T_{Skin} = 300 °C in press) and joined with the core under a pressure of 0.2 MPa. For the customised foam a core compaction distance of 2 mm is applied.

Both methods seem to be feasible as the core is strongly joined to the skins, see Figure 117.



a) **b)**

Figure 117: Skin and core bond with the a) 'As-is' foam and b) Customised foam

Figure 118 shows the whole shaped sandwich panel, where both skins are joined to the core.

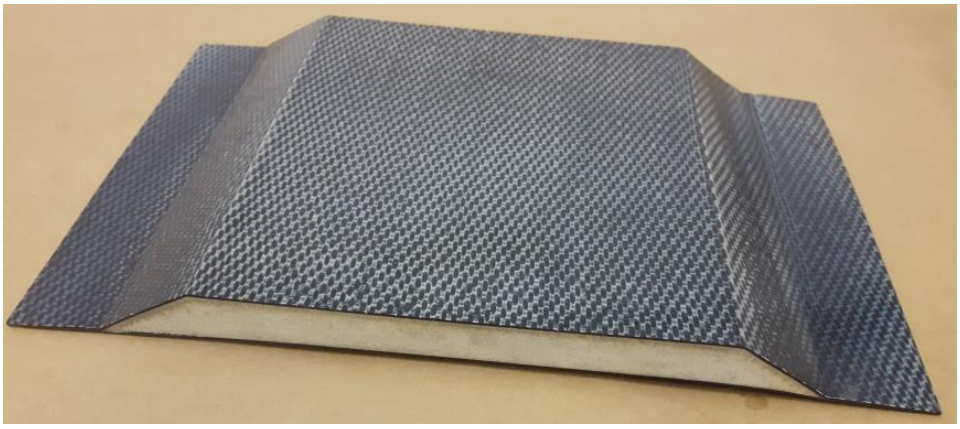


Figure 118: Simplified shaped sandwich panel

9.6 DISCUSSION

Taking a detailed look into the boundary layers of the cores (Figure 117), differences in the cell structures can be observed. Joining the core with an 'as-is' foam causes compaction of the cells in the ramp zone to a high extent. Figure 119 shows a microscopic picture of the ramp zone of the core, which highlights the high extent of cell compaction. In contrast, customising the core reduces the extent of core compaction, as shown in Figure 120.

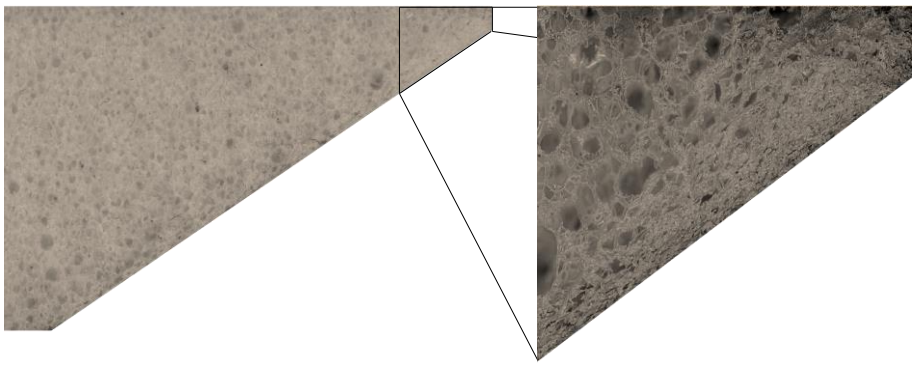


Figure 119: Cell deformation caused by joining with initial foam

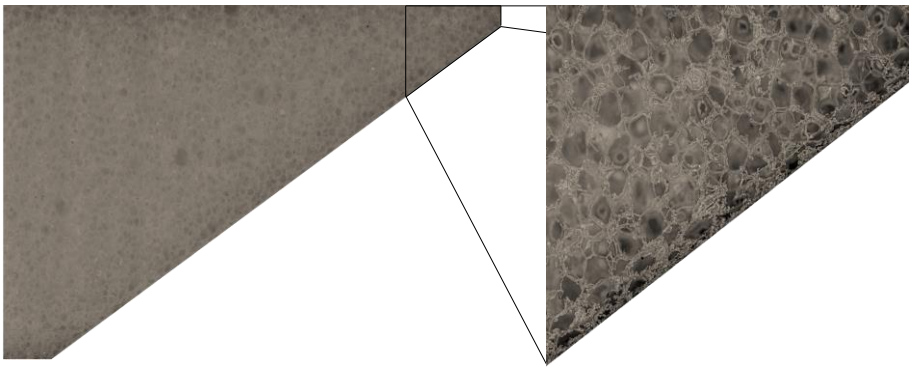


Figure 120: Cell deformation caused by joining with customised foam

In chapter 6.3.2 it is shown that core compaction is detrimental to the quality of the core, and as a result to the quality of the entire sandwich. It is shown that a higher compaction of the cells leads to a sharper gradient between compacted cells in the boundary layer and original cells in the core centre. Failure in the transition zone between affected and unaffected cells of the core occurs at lower loads in comparison to cores with unaffected cells. Therefore, it has to be decided from case to case if a decrease in performance or the manufacturing cycle time has priority for the application.

9.7 REALISATION OF DEMONSTRATOR

Based on the results for fusion bonding CF/PEEK skins and PEI foam core, as well as results and experience gained during the realisation of the simplified shaped sandwich panel, the shear panel is successfully manufactured at a skin temperature of 300 °C, a core compaction distance of 2 mm, and a pressure of 0.2 MPa, see Figure 121. Here, a customised foam is used, which has an excess of 2 mm in each direction to enable a compaction distance of 2 mm.

Figure 122 shows the cross section of the manufactured shear panel, which reveals that an even and strong bond between the skins and core has been achieved. However, by taking a detailed look into the peripheral areas of the panel, where upper and lower skin touch, an insufficient bond can be detected at some spots, see highlighted in Figure 122.

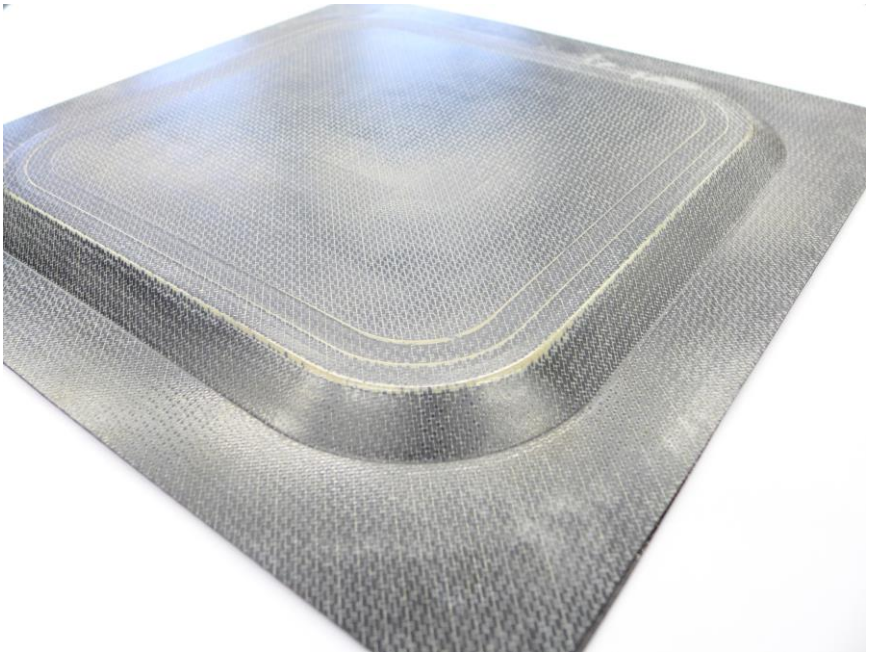


Figure 121: Shaped shear panel

The insufficient bond might be explained by periphery effects such as higher heat loss at the outer area or insufficient contact due to tool deviations. Furthermore, it has to be stated that the process window which was derived and defined in the previous chapters is valid for a skin-to-core-bond. The process window might likely not be valid for skin-to-skin bonding, since the material properties and surrounding conditions are different. However, it is assumed that a solution can be found by further investigations and adaptation of the manufacturing process such as an industrialised heating and transport system.

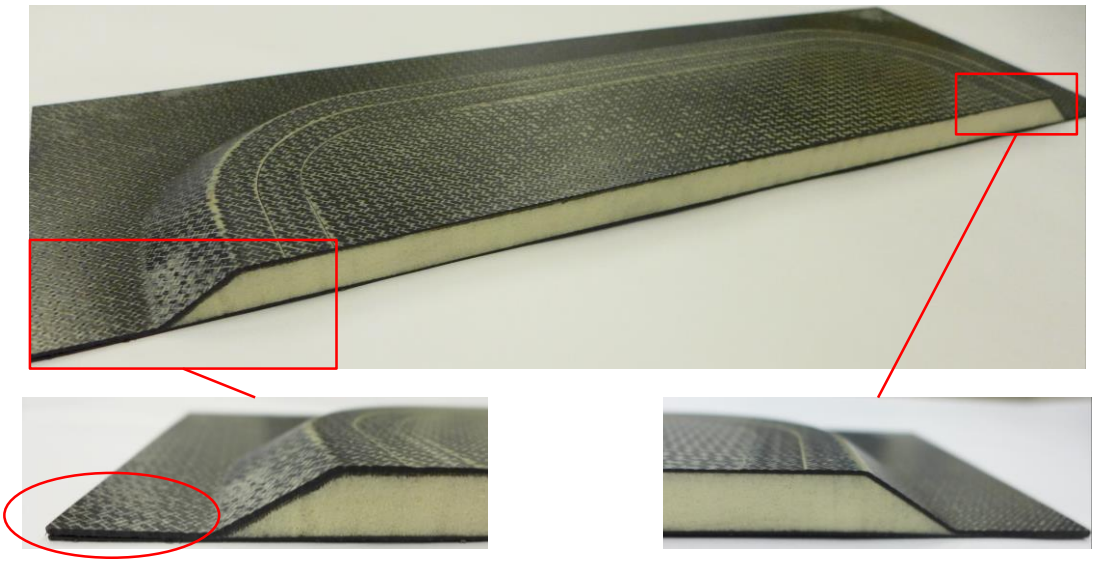


Figure 122: Cross section of shear panel

10. CONCLUSION AND OUTLOOK

The aim of this study is the development of a manufacturing process for full thermoplastic sandwich structures, suitable for structural helicopter applications. The aim in doing so is to reduce manufacturing cycle times in comparison to state-of-the-art sandwich structures and to fulfil the requirements related to mechanical performance, design freedom as well as manufacturing and in-service conditions. Furthermore, the possibility of applying foam core structures instead of honeycomb materials is pursued, since foam cores require less post processing after production and less maintenance in service compared to honeycomb sandwiches. Nevertheless, it is accepted and considered in the requirements that the application of foam structures will lead to performance disadvantages in comparison to the use of honeycomb cores.

To guarantee the principle of function of sandwich structures, a good bond between skins and core is required. This means aiming to realise a skin-to-core bond that is stronger than the core strength itself. Published investigations show that fusion bonding of skins and core is a promising technology for thermoplastic sandwich materials, since a bond strength equalling the bulk material strength can be achieved, while the process requires minimal preparation steps such as surface treatment and can be conducted in short cycle times. However, investigations into the development of sandwich structures by means of fusion bonding have not yet been conducted with materials, which fulfil the defined requirements and which are suitable for structural helicopter applications. The structures developed up to today either consist of commodity polymers which feature a low performance or in the case of high performance polymer based sandwiches, the sandwich structures present limitations concerning design freedom, or core thickness.

Therefore, to reach the goal of this study carbon fibre reinforced Polyetheretherketone (CF/PEEK) skins and a Polyetherimide (PEI) foam core are selected according to the materials state-of-the-art. Based on a manufacturing process evaluation, non-isothermal compression moulding is seen to be an adequate process in this study for joining skins and core in short cycle times while reducing the risk of collapse due to the separate heating stage of the skins before joining.

However, first experimental trials revealed that fusion bonding, which requires both constituents to be in the molten state during joining, is not readily possible due the wide temperature gap in softening PEEK and PEI. This causes challenges such as skin de-consolidation and core collapse.

To prevent these issues and to allow for the successful production of CF/PEEK – PEI foam sandwiches, the manufacturing process is adapted by means of superficial PEI enrichment of the CF/PEEK skins according to the ‘Thermabond’ process. In doing so, the skins can be fusion bonded to the core at temperatures below the melting temperature of the PEEK matrix, but above the glass transition temperature of PEI, in order to soften the PEI enriched surface as well as the core surface. As a result, core collapse and skin de-consolidation can be avoided.

In order to understand the governing mechanisms of a fusion bond, the manufacturing process is investigated theoretically. A model based on ‘intimate contact’ and ‘healing’ is deduced for the non-isothermal compression moulding process, which allows the prediction of the bond

strengths depending on different skin and core temperatures. The model predicts that sandwiches manufactured with skin temperatures above ~290 °C and cores kept at room temperature will feature a sufficient bond strength, which is higher than the tensile strength of the core. In addition, the model predicts that heating the core will probably have a positive effect on the bond strength.

Verification of the model with experimental trials proves the feasibility of a successful sandwich production, and shows that the modelling approach successfully predicts the failure modes of the sandwiches that occur under load. In the cases where the interface tensile bond strength is below the tensile core strength the model allows an accurate prediction of the bond strength and the failure mode, while in some cases, where the bond strength is above the core strength, the model is only able to predict the failure mode based on the weakest link, which in these cases is the core and not the interface. Furthermore, the experimental trials show that extensive heating of the core (200 °C) leads to core collapse, which is not considered in the model. In order to avoid incorrect model predictions due to the core collapsing effect, it seems useful to take a detailed look at the heat flow from the skins into the core during processing followed by an analysis of the thermal stability of the foam. In doing so, it is recommended to keep the centre of the core below its softening temperature.

Based on the proposed process window, a complementary characterisation of the skin-to-core bond, core structure and the entire sandwich is presented. The influences of several process parameters, in particular varying skin temperatures *(T_{Skin}* = 300 °C – 320 °C*)*, different core compaction distances *($d_{compaction}$* = 1 mm - 3 mm*)* as well as varying PEI film thicknesses *(h_{PEI}* = 125 µm and 175 µm*)* on the tensile, compression, shear, flexural and impact properties are determined. The core temperature *(T_{Core})* is not further investigated.

The sandwich characterisation shows that the proposed process window mostly enables a fusion bond strength between skins and core which exceeds the core strength and in most cases and leads to cohesive failure of the core. However, in the case of a minimal core compaction distance of 1 mm, contact between skins and core cannot be ensured, leading to an insufficient bond. Moreover, analysis of the core structure revealed that the processing parameters significantly influence the thermoplastic core cell structure close to the core surface, which is defined as the boundary layer. A change of the core cell structure in the boundary layer leads to a weakening of the core and failure predominantly occurs in the interface between affected and original cells. Here, the experimental trials show the higher the cell compaction, the lower the core performance. In addition, a higher core compaction leads to a higher density of the core. As a result, a core compaction distance of 2 mm seems to be suitable for the manufacturing process. Furthermore, analysis of the core structure shows that at higher skin temperatures such as 320 °C the core centre collapses and stretches the cell in the boundary layer of the core, which softens the gradient between compacted and original cells resulting in a slight improvement of the performance. However, due to uncontrolled core collapse at skin temperatures of 310 °C and 320 °C, the process is considered not reproducible. Therefore, a skin temperature of 300 °C is evaluated to be the best fit for the manufacturing process. Increasing the film thickness of the skins does not lead to a significant improvement of the performance, though it increases the weight of the sandwiches. Therefore, a PEI film thickness of 125 µm is preferred.

In order to evaluate the CF/PEEK–PEI foam sandwiches, a skin temperature of 300 °C, a core kept at room temperature, 2 mm core compaction distance and skins enriched with a 125 µm PEI film are selected. The sandwich structures are compared in a first step to state-of-the-art sandwiches and comparable foam based sandwiches. As references, prepreg-Nomex® honeycomb sandwiches (core density of 48 kg/m³), manufactured with an autoclave process and Polymethacrylimide (PMI) foam based sandwiches with foam densities of 63 kg/m³ manufactured by resin transfer moulding are taken. The comparison shows the significant superior performance of the Nomex® based sandwiches concerning all properties. Furthermore, the comparison reveals that the PMI sandwich structures also show better properties related to weight than the CF/PEEK-PEI foam sandwiches.

In a second step, the evaluation of mechanical performance according to the requirements reveals that CF/PEEK-PEI foam sandwich structures with a 60 kg/m³ core feature a compression strength which lays approximately 45 % below the required compression strength, while the shear strength is approximately 20 % below the required 1.1 MPa. By applying a PEI foam core with a density of 110 kg/m³, it is assumed that the performance can be increased almost to the required values. However, by applying a core with a higher density the weight will be further increased. CF/PEEK-PEI sandwich already show the highest areal weight in the assessment. Nevertheless, the evaluation reveals that the CF/PEEK-PEI foam sandwiches feature a strong skin-to-core bond which is above the required strength by a factor of 2.65 and therefore in most cases leads to failure within the core. In comparison, the Nomex® based and PMI foam based sandwich specimens often fail within the interface. The comparison shows that in the case of the Nomex® and PMI sandwich specimens the skin-to-core bond is the weakest link, while for the CF/PEEK-PEI foam sandwiches the core represents the weakest link.

Based on these results, a follow-up study is performed to find a solution to strengthen the core. Two concepts, based on the integration of pins, which are fusion bonded to the skins and the core surface, are developed. The introduction of pins either orthogonally or diagonally to the skin plane, leads to an improvement of the compression and shear properties by a factor of 10 and 1.72 respectively. Normalised to the weight, significantly improved specific compression strengths can be still achieved. Therefore, the pinning concept looks especially promising when applied locally, for example in highly loaded areas. Nevertheless, additional cost for the modification process need to be considered.

In regard to the cycle times of thermoplastic materials in combination with foam cores, the manufacturing times can be significantly decreased in contrast to the manufacturing of prepreg-Nomex® sandwiches. By applying thermoplastic skins and a thermoplastic core, a cycle time reduction of 46 % can be achieved, while the infusion of the PMI foam leads to a reduction of the cycle times of up to 24 %. However, the fusion bond process cannot totally fulfil the envisaged process time of 4 hours. Indeed, the process cycle time assessment is based on laboratory results, which means that several manufacturing steps are performed manually or without industrialised processing abilities. As a result, it assumed that the cycle time can be further reduced by more than 20 %, when implemented as a serial production process.

Finally, this thesis shows the feasibility of the realisation of full thermoplastic shaped sandwich panel. Therefore, in a first step the process window for forming the skins and core individually

is defined. By merging the individual forming process windows and the fusion bonding process window, it becomes obvious that fusion bonding and simultaneously forming of the CF/PEEK-PEI sandwiches structures is not feasible. The processing window gap between the individual sandwich constituents is too wide to realise a formed panel in one processing step. Furthermore, based on the individual forming process windows the approach to thermoform a 2D sandwich into a formed sandwich panel does not seem feasible either. Therefore, skins and core are formed separately before being fusion bonded. The realisation of a shaped shear panel, which is defined as the target structure, by a two-step approach is finally proven.

10.1 OUTLOOK

For the implementation of novel materials and structures in the aviation industry, a quality and reproducibility assurance is of immense importance. As shown in this study, the quality of TPC sandwiches is highly dependent on the processing parameters. Therefore, a technique has to be developed which allows inline monitoring of the process parameters such as skin temperature. A promising technology could be the integration of micro sensors on the PEI film of the skins, which allows for monitoring of heat and pressure during processing and which can remain in the sandwich construction after processing. Micro sensors printed on PEI films have already been developed by Airbus Group Innovations.

Furthermore, the mechanical characterisation with a subsequent evaluation reveals that the performance of the developed CF/PEEK-PEI foam sandwiches is low compared to the state-of-the-art sandwiches and cannot totally fulfil all envisaged requirements. However, the process offers the advantage of reducing the manufacturing cycle time and costs significantly and therefore looks promising in replacing prepreg-Nomex® sandwiches in applications where manufacturing costs are of higher significance than the mechanical performance of the structure. In order to also find application in heavier loaded elements, two concepts, based on the integration of pins into the core to strengthen the structures are developed and their potential is shown in first trials. To take further advantage of these concepts, more detailed investigations concerning pin amount, pin diameter, etc. should be performed in the future.

Finally, the realisation of the shaped panel proved the feasibility of the production of shaped sandwich parts. A good bond between skins and core was achieved, though skin-to-skin joining at some locations could not be performed sufficiently well. This lack of bonding is related to periphery effects and due to the fast heat transfer from the skin into the cold mould. However, it is assumed that a modification of the mould and adaptation of heating elements to limit skin cooling during transfer can be solved by an industrialised process and can lead to the successful production of shaped sandwich panels.

11. REFERENCES

1. HERRMANN, A. S., ZAHLEN, P. C. and ZUARDY, I. Sandwich structures technology in commercial aviation- Present Applications and Future Trends. In: THOMSEN, O.T. and BOZHEVOLNAYA, E. (eds.), *Sandwich Structures 7: Advancing with Sandwich Structures and Materials*. Aalborg, Denmark, 29 -21 August 2005. Springer Netherlands, p. 13–26.
2. *http://philschatz.com/anatomy-book/resources/621_Anatomy_of_a_Flat_Bone.jpg* [online]. [Accessed 13 December 2016] Available from: http://philschatz.com/anatomy- book/resources/621_Anatomy_of_a_Flat_Bone.jpg
3. DEUTSCHES INSTITUT FÜR NORMUNG E.V. *DIN 53290 - Testing of sandwiches, definition of terms*. Berlin: Beuth Verlag GmbH, February 1992.
4. PETRAS, A. *Design of sandwich structures*. [PhD Thesis] Cambridge, England: Robinson College, 1998.
5. CAMPBELL, F. *Manufacturing Technology for Aerospace Structural Materials*. Amsterdam: Elsevier, 2006.
6. AKERMO, M. and ASTRÖM, B.T. Modelling of compression moulding of all-thermoplastic honeycomb core sandwich components. In: *Proceedings of 41st International SAMPE Symposium*. Anaheim, USA, 24 - 28 March1996. p. 1372–1381.
7. FAIRBAIRN, W. *An account of the Construction of the Britannia and Conway Tubular Bridges*. London: John Weale, 1849.
8. VAN TOOREN, M. J.L. *Sandwich Fuselage design*. [PhD Thesis] Delft, Netherlands: TU Delft, 1998.
9. VON KARMAN, T. and STOCK, P. GB235884 - Improvements in Building Materials for Lightweight Structures. GB235884. 17 June 1924.
10. VINSON, J.R. Sandwich Structures: Past, Present, and Future. In: THOMSEN, O.T., BOZHEVOLNAYA, E. and LYCKEGAARD, A. (eds.), *Sandwich Structures 7: Advancing with Sandwich Structures and Materials*. Aalborg, Denmark, 29 - 31 August 2005. Springer Netherlands, p. 3–12.
11. GORDON, J.E. *Structures: or, why things don't fall down*. Harmondsworth: Penguin Books, 1978.
12. BANSEMIR, H. Lightweight design of composite sandwich structures. In: DENBRATT, I. (ed.), *Sustainable Automotive Technologies 2014: proceedings of the 6th ICSAT*. Gothenburg, Sweden, September 2014, Springer International Publishing.
13. NATIONAL AERONUATICS AND SPACE ADMINISTRATION. Apollo 11 Command and Service Module (CSM). [online]. [Accessed 14 December 2016]. Available from: http://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1969-059A
14. ZAHAVI, Y., BECKMANN, M. J. and GOLOB, T.F. DOT-RSPA-DPB 10/7: *The UMOT/ Urban Interactions*. Technical report. U.S. Department of transportation, 2007.
15. INTERNATIONAL CIVIL AVIATION ORGANIZATION. *Economic development 2015: Air transport yearly Monitor* [online]. [Accessed 12 December 2016]. Available from: http://www.icao.int/sustainability/Documents/Yearly%20Monitor/yearly_monitor_2015.pdf

16. LEE, J.J., LUKACHKO, S.P., WAITZ, I. A. and SCHAFER, A. Historical and future trends in aircraft performance, cost, and emissions. *Annual Review of Energy and the Environment. 2001*. Vol. 26, p. 167–200.

17. HERBECK, L., KLEINEBERG, M. and SCHÖPPINGER, C. Foam cores in RTM structures: manufacturing aid or high-performance sandwich. In: *Proceedings of 23rd SAMPE International conference*. Paris, France, 9 - 11 April 2002.

18. KLEBA, I., HABERSTROH, E. and KRAEMER, A. All-phenolic sandwich structures for aircraft interior applications. In: *Proceedings of 46TH INTERNATIONAL SAMPE SYMPOSIUM AND EXHIBITION*. Long Beach, USA, 06 - 10 May 2001. p. 2562–2576.

19. SCHÜRMANN, H. *Konstruieren mit Faser-Kunststoff-Verbunden*. 2. Berlin, Heidelberg: Springer Verlag, 2007.

20. COMPOSITEWORLD'S MODERATORS. Donauwörth as composites pioneer. [online]. 9 February 2015. [Accessed 15 December 2016]. Available from: http://www.compositesworld.com/blog/post/donauwrth-as-composites-pioneer

21. SEIBERT, H.F. Applications for PMI foams in aerospace sandwich structures. *Reinforced Plastics*. January 2006. Vol. 50, no. 1, p. 44–48.

22. ASTRÖM, B.T., AKERMO, M., CARLSSON, A. and MCGARVA, L.D. The all-thermoplastic sandwich concept. In: *Sandwich Construction 4: Fourth International Conference on Sandwich Construction*. Stockholm, Sweden, 09 - 11 June.1998. p. 705–718.

23. ASTRÖM, B.T. Sandwich manufacturing: past, present, and future. In: *Sandwich Construction 4: Fourth International Conference on Sandwich Construction*. Stockholm, Sweden, 09 - 11 June 1998. p. 697–704.

24. HSIAO, H.M. and BUYNY, R.A. Core Crush Problem in the Manufacturing of Composite Sandwich Structures: Mechanism and Solutions. *AIAA Journal*. April 2006. Vol. 44, no. 4, p. 901–907.

25. IBARRA-CASTANEDO, C., MARCOTTE, F. and GENEST, M. Detection and characterization of water ingress in honeycomb structures by passive and active infrared thermography using a resolution camera. In: *Proceedings of 11th International Conference on Quantitative InfraRed Thermography*. Naples, Italy, 11 – 14 June 2012.

26. HEALTH AND SAFETY EXECUTIVE. *Designing and operating safe chemical reaction processes*. HSE Books, 2000.

27. OCCUPATIONAL SAFETY AND HEALTH AMINISTRATION. Polymer Matrix Materials: Advanced Composites- Health Hazards. [online]. https://www.osha.gov/dts/osta/otm/otm_iii/otm_iii_1.html#6. [Accessed 15 December 2016]. Available from: https://www.osha.gov/dts/osta/otm/otm_iii/otm_iii_1.html#6

28. SCHAFER, A. and VICTOR, D. G. The future mobility of the world population. *Transportation Research Part A*. December 1998. Vol. 34, p. 171–205.

29. CARRIGER, Doug. Market Cycles & OEM Forecast. *Helicopter Investor Miami* [online]. 23 October 2015. [Accessed 14 December 2016]. Available from: http://helicopterinvestor.com/wp-content/uploads/2015/10/2-Keynote-AIRBUS-helicopter.pdf

30. LEAHY, J. Global Market Forecast. Mapping demand 2016-2035. [online]. [Accessed 14 December 2016]. Available from: http://www.airbus.com/company/market/global-market-forecast-2016-2035/

31. TOPHAM, G. Airbus flies past Boeing in aircraft orders. [online]. 12 January 2016. [Accessed 15 December 2016]. Available from: https://www.theguardian.com/business/2016/jan/12/airbus-overtakes-boeing-in-aircraft-orders

32. KAUFMANN, M. *Cost/Weight Optimization of Aircraft Structures*. [PhD Thesis] Stockholm, Sweden: KTH, 2008.

33. ASIEDU, Y. and GU, P. Product life cycle cost analysis: state of the art review. *International Journal of Production Research*. 1998. Vol. 36, no. 4, p. 883–908.

34. PARLEVLIET, P. and WEIMER, C. Thermoplastic high performance composites: environmental requirements on future helicopter airframes. In: *Proceedings of 18th International Conference on Composite Materials*. Edinburgh, Scotland, 27 - 31 July 2009.

35. EBERTH, U., PUDENZ, C. and SCHWARZE, H. Life cycle assessment for helicopter airframe structures. In: *ERF Document Repository.* Paris, France, 7 September 2010. p. 126–129.

36. EHRENSTEIN, G.W. *Polymere Werkstoffe*. 2. München-Wien: Karl-Hanser Verlag, 1992.

37. OFFRINGA, A. and DAVIES, C. Gulfstream V Floors - Primary Aircraft Structure in Advanced Thermoplastics. *Journal of Advanced Materials*. January 1996. p. 2–10.

38. MC GARVA, L. *Thermoplastic composite sandwich components: Experimental and numerical investigation of manufacturing issues*. [PhD Thesis] Stockholm, Sweden: Royal Institute of Technology, 2002.

39. AKERMO, M. and ASTROM, B. T. Experimental Investigation of Compression Molding of Glass/PP-PP Foam Core Sandwich Components. *Journal of Thermoplastic Composite Materials*. 1 July 1999. Vol. 12, no. 4, p. 297–316.

40. KULANDAIVEL, P.P. *Manufacturing and performance of thermoplastic composite sandwich structures*. [PhD Thesis] Nottingham, England: University of Nottingham, 2006.

41. RED, C. The Outlook for Thermoplastics in Aerospace Composites, 2014-2023. *High-Performance Composites* [online]. 9 January 2014. [Accessed 16 December 2016]. Available from: http://www.compositesworld.com/articles/the-outlook-for-thermoplastics-in-aerospace-composites-2014-2023

42. OFFRINGA, A. Application of advanced thermoplastics. In: *Proceedings of International Symposium on Advanced Materials for Lightweight Structures*. Noordwijk, Netherlands, 27 March 1992.

43. PARLEVLIET, Patricia and WEIMER, Christian. Ecodesigned thermoplastic composite helicopter airframe structures. In: *Proceedings of SETEC 12 - 7th international technical conference*. Lucerne, Switzerland,19 - 20 September 2012.

44. GOLDMANN, F. Die leichte Balance. *Kunststoffe*. September 2010. Vol. 9/2010.

45. ALTSTÄDT, V., DIEDRICHS, F. and LENZ, T. Polymer foams as core materials in sandwich laminates (comparison with honeycomb). *Polymer and polymer composites*. July 1998. Vol. 6, no. 5, p. 295–304.

46. PAPPADÀ, S., RAMETTA, R., PASSARO, A., LANZILOTTO, L. and MAFFEZZOLI, A. Processing, mechanical properties, and interfacial bonding of a thermoplastic core-foam/composite-skin sandwich panel. *Advances in Polymer Technology*. 2010. Vol. 29, no. 3, p. 137–145.

47. RENAULT, Thierry. Sandwiform®: Thermoplastic composites sandwich structures. *Society of Manufacturing engineers*. 2002. Vol. EM02-126.

48. DUCHENE, R. US005683782A - Process for producing of a honeycomb structure and a honeycomb structure so produced. US005683782A. 13 September 1995.

49. MUZZY, J., PFAENDTER, J., SHAW, B. and HOLTY, D. Thermoplastic composite sandwich panels. In: *Proceedings of Automotive Composite Conference*. Troy, USA, 19 - 20 September 2001.

50. CABRERA, N.O., ALCOCK, B. and PEIJS, T. Design and manufacture of all-PP sandwich panels based on co-extruded polypropylene tapes. *Composites Part B*. October 2008. Vol. 39, p. 1183–1195.

51. BASF. *Erstes Serienbauteil aus Ultratec, dem Schaumstoff aus Ultrason von BASF* [online]. BASF press release. 2003. [Accessed 27 May 2013]. Available from: http://www.basf.de/de/produkte/kstoffe/news/pm.htm?printview=on&pmid=1344

52. AKERMO, M. and ASTRÖM, BT. Modeling compression molding of all-thermoplastic honeycomb core sandwich components. Part A: Model development. *Polymer Composites*. April 2000. Vol. 21, no. 2, p. 245–256.

53. AKERMO, M. and ASTRÖM, B. Modeling Compression molding of All-Thermoplastic Honeycomb Core Sandwich components. Part B: Model Verification. *Polymer Composites*. April 2000. Vol. 21, no. 2, p. 257–267.

54. WIHAG-COMPOSITES. *MonoPan® - a new innovation material technology*. 14 April 2005

55. WIHAG COMPOSITES. *MonoPan® - The Future in Material Technology* [online]. [Accessed 21 August 2014]. Available from: www.monopan.ca/docs/MonoPan.pdf

56. BROWN, K., BROOKS, R., WILLIAMSON, P. and PRICE, C. Development of a novel thermoplastic composite sandwich structure for a rail application. In: *Proceedings of SAMPE Europe - 29th International Conference and Forum*. Paris, France 31 March 2008. p. 220–225.

57. SKAWINSKI, O., BINETRUY, C., KRAWCZAK, P., GRANDO, J. and BONNEAU, E. All-Thermoplastic Composite Sandwich Panels – Part I: Manufacturing and Improvement of Surface Quality. *Journal of Sandwich Structures and Materials*. September 2004. Vol. 6, no. 5, p. 399–421.

58. PAPPADÀ, S., RAMETTA, R., LANZILOTTO, L. and MAFFEZZOLI, A. Effect of manufacturing process and skin-core adhesion efficiency on the mechanical properties of a thermoplastic sandwich. In: *Proceedings of ICCM 17*. Edinburgh, Scotland, 27- 31 July 2009. p. IB6:6.

59. BROWN, K., BROOKS, R., WARRIOR, N. A. and KULANDAIVEL, P. P. Modelling the impact behaviour of thermoplastic composite sandwich structures. In: *Proceedings of 16th international conference of composite materials*. Kyoto, Japan, 03 - 08 July 2007.

60. BROOKS, R., KULANDAIVEL, P., and RUDD, C. D. Skin consolidation in vacuum moulded thermoplastic composite sandwich beams. In: Proceedings of *8th International Conference on Sandwich Structures*. Porto, Portugal, 06 - 08 May 2008. p. 627–637.

61. PASSARO, A., CORVAGLIA, P., MANNI, O., BARONE, L. and MAFFEZZOLI, A. Processing-properties relationship of sandwich panels with polypropylene-core and polypropylene-matrix composite skins. *Polymer Composites*. June 2004. Vol. 25, no. 3, p. 307–318.

62. MAYER, C., OSTGATHE, M., BREUER, U. and NEITZEL, M. High speed manufacturing of knitted thermoplastic composite sandwich systems. In: *Proceedings of 17th international SAMPE Europe Conference*. Basel, Switzerland, 28 - 30 May 1996.

63. KULANDAIVEL, P., BROOKS, R., DUNMORE, M., RUDD, C. and MCNALLY, D. Processing and performance of thermoplastic composite sandwich beams for automotive applications. In: *Proceedings of 37th International SAMPE Technical Conference*. Seattle, USA, 31 October - 03 November 2005.

64. NOWACKI, J., NEITZEL, M. and MITSCHANG, P. Potential für Serienfertigung-Thermoplastische Sandwich - Strukturbauteile in einem Schritt geformt. *KU Kunststoffe*. 2001. Vol. Jahr 91, p. 92–95.

65. REYNOLDS, N., PHARAOH, M, PAPADAKIS, N., SMITH, G. and PRICE, C. All-thermoplastic Composite Parts for the Automotive Industry Part A: Manufacture and Testing. In: *Proceedings of 4th Conference on Materials for Lean Weight Vehicles: LWV 4*. Gaydon, England, 30 - 31 October 2001.

66. MCGARVA, L.D. and ÅSTRÖM, B.T. Experimental investigation of compression moulding of glass/PA12-PMI foam core sandwich components. *Composites Part A: Applied Science and Manufacturing*. October 1999. Vol. 30, no. 10, p. 1171–1185.

67. MCGARVA, Lance D. and ASTRÖM, B. Tomas. Compression moulding of thermoplastic composite sandwich components. In: *Proceedings of ICCM 12*. Paris, France, 05 - 09 July 1999.

68. TRENDE, A. and ASTRÖM, B. T. Heat Transfer in compression molding of thermoplastic composite laminates and sandwich panels. *Journal of Thermoplastic Composite Materials*. January 2002. Vol. 15, p. 43–63.

69. BREUER, U., OSTGATHE, M. and NEITZEL, M. Manufacturing of all-thermoplastic sandwich systems by a one-step forming technique. *Polymer Composites*. June 1998. Vol. 19, no. 3, p. 275–279.

70. AKERMO, M. and ASTRÖM, B.T. Modelling face-core bonding in sandwich manufacturing: Thermoplastic faces and rigid closed-cell foam core. *Composites Part A: Applied Science and Manufacturing*. 1998. Vol. 29, no. 5–6, p. 485–494.

71. ROZANT, O, BOURBAN, P.-E and MANSON, J.-A.E. Manufacturing of three-dimensional sandwich parts by direct thermoforming. *Composites Part A: Applied Science and Manufacturing*. November 2001. Vol. 32, no. 11, p. 1593–1601.

72. ROZANT, O., BOURBAN, P.-E. and MANSON, J.-A. E. Experimental and numerical investigation of the forming of thermoplastic sandwiches. In: *Proceedings of ICCM 12*. Paris, France, 05 - 09 July 1999

73. ROZANT, O., BOURBAN, P. -E., MANSON, J. -A.E. and DREZET, J. -M. Pre-Heating of Thermoplastic Sandwich Materials for Rapid Thermoforming. *Journal of Thermoplastic Composite Materials*. November 2000. Vol. 13, no. 6, p. 510–523.

74. ROZANT, O., VOLLAN, A., SPICHTIG, J., BOURBAN, P.-E. and MANSON, J.-A.E. Development of an explicit finite element solution for the forming simulation of thermoplastic sandwiches. In: *Proceedings of 3rd Swiss CAD-FEM Users' Meeting'98*. Lucerne, Switzerland, 18 - 19 June 1998.

75. BROUWER, W. D. Foam forming: A promising technology for the volume manufacture of ac sandwich components. In: *Proceedings of 6th annual ASM/ESD Advanced Composites Conference*. Detroit, USA, 08 - 11 October 1990.

76. PROVO KLUIT, P.-W. C. *The Development of In-Situ Foamed Sandwich Panels* [PhD Thesis] Delft, Netherlands: TU Delft, 1997.

77. FITS-TECHNOLOGY. http://www.fits-technology.com/ [online]. [Accessed 17 September 2014]. Available from: http://www.fits-technology.com/

78. FITS-TECHNOLOGY. *Technical Data - FITS panels* [online]. [Accessed 17 September 2014] Available from: www.fits-technology.com/technicaldata.html

79. OFFRINGA, A. Thermoplastic aircraft floor panels, technologies, and applications. *Journal of Advanced Materials*. 1995. Vol. 26, p. 12–18.

80. MÜHLBACHER, M., HORNFECK, C., NEUMEYER, T. and ALTSTÄDT, V. Thermoplastische Sandwichstrukturen aus Luftfahrtmaterialien. *Lightweight design*. 2016. Vol. 4, p. 44–49.

81. REYES, G. and RANGARAJ, S. S. Interfacial fracture properties of novel carbon foam structures. In: *Proceedings of 41st SAMPE Fall Technical Conference*. Wichita, USA,19 - 22 October 2009.

82. HUEBNER, F. US4957577 - Method for making welded honeycomb core. US4957577. 4 April 1988.

83. PFLUG, J., VERPOEST, I., BRATFISCH, P. and VANDEPITTE, D. Thermoplastic folded honeycomb cores - cost efficient production of all thermoplastic sandwich panels. In: *Proceedings of ICCM13*. Beijing, China, 25 - 29 June 2001.

84. FISCHER, S., HEIMBS, S., KLICHERT, S. and KLAUS, M. Sandwich structures with folded core: Manufacturing and mechanical behavior. In: *Proceedings of SAMPE Europe 30th. International Jubilee Conference and Forum*. Paris, France, 23 - 25 March 2009.

85. KLETT, Y. Foldcore. [online.] [Accessed 03 February 2017]. Available from: *www.foldcore.eu*.

86. KÖPPL, T. *Halogenfrei flammgeschütztes Polybutylenterephtalath und dessen Verarbeitung zu Polymerschäumen*. [PhD Thesis]. Bayreuth, Germany: University of Bayreuth, 2014.

87. FRISCH, K. and KLEMPNER, D. *Handbook of Polymeric Foams and foam Technology*. München: Hanser, 1991.

88. COLTON, J.S. The nucleation of microcellular foams in semi-crystalline thermoplastics. *Materials and Manufacturing Processes*. 1989. Vol. 4, p. 253–262.

89. PASSARO, A., CORVAGLIA, P., MANNI, O., BARONE, L. and MAFFEZZOLI, A. Processing and characterization of PP-based thermoplastic sandwich panels. In: *Proceedings of 23rd International SAMPE Europe Conference*. Paris, France 04 - 11 April 2002.

90. FAN, X., LI, Y., LI, J., YAN, C. and LI, K. Modeling of heat conduction in thermoplastic honeycomb core/face sheet fusion bonding. *Chinese Journal of Aeronautics*. 2009. No. 22, p. 685–690.

91. MACALUSO, C., VANDEPITTE, D. and VERPOEST, I. Deepdrawing FE-simulations for thermoplastic sandwich structures. *International journal of material forming*. 2008. Vol. 1, no. No. 1, p. 907–910.

92. BROOKS, R., KULANDAIVEL, P.P. and RUDD, C. Vacuum moulding of thermoplastic composite sandwich beams. In: *Proceedings of International SAMPE Europe Conference 2004*. Paris, France 30 March - 01 April 2004. p. 494–500.

93. ZEPF, H.P. and SPRENGER, K.-H. Composite-Sandwichbauteile durch Zwischenspritzen von geschäumten Thermoplasten. In: *Proceedings of 28. AVK Tagung*. Baden-Baden, Germany, 01 - 02 October 1997. p. 1–10.

94. GARDINER, G. Move over honeycomb, thermoplastic sandwich is commercialized as DYNATECH. *Composite world* [online]. 18 April 2014. [Accessed 17 December 2016]. Available from: www.compositesworld.com/blog/post/move-over-honeycomb-thermoplastic-sandwich-is-commercialized-as-dynatech

95. EVONIK Resource Efficiency GmbH. Technical information – ROHACELL® RIST - HT. [online] June 2016 [Accessed 2 January 2017]. Available from: http://www.rohacell.com/sites/lists/RE/DocumentsHP/ROHACELL-RIST-HT-technical-information-en.pdf

96. GAUGLER&LUTZ OHG. *Airex® R82 Materialdatenblatt DE 2011 V02* [online]. July 2011. [Accessed 4 July 2016]. Available from: http://www.gaugler-lutz.de/leicht-sandwichbau/airex-kernmaterial/airex-r82.html

97. TUBUS-BAUER. *Datasheet Tubus Core*. [online] February 2015. [Accessed 2 January 2017]. Available from: http://redaxo-web.tubus-bauer.de/files/2016-09-03-pei4_0-48c-144c_english.pdf

98. PIZZI, A. and MITTAL, K.L. *Handbook of adhesive technology*. New York: Marcel Dekker, Inc., 1994.

99. WINGFIELD, J.R.J. Treatment of composite surfaces for adhesive bonding. *International Journal of Adhesion and Adhesives*. July 1993. Vol. 13, no. No. 3, p. 151–156.

100. AGEORGES, C., YE, L. and HOU, M. Advances in fusion bonding techniques for joining thermoplastic matrix composites: a review. *Composites Part A: Applied Science and Manufacturing*. June 2001. Vol. 32, no. 6, p. 839–857.

101. HASLAM, E.B. *Development of bonding methods and energy absorption of sandwich panels for thermoplastic advanced composites* [Master thesis] Utah, USA: University of Utah, 2012.

102. 3M-AEROSPACE-AND-AIRCRAFT MAINTENANCE DEPARTMENT. *3M Scotch-Weld™ Structural Adhesive Film AF 163-2 Technical Datasheet*. [online] November 2009. [Accessed 04 January 2017]. Available from: http://multimedia.3m.com/mws/media/282041O/3m-scotch-weld-structural-adhesive-film-af-163-2-af-163-3.pdf

103. OURAHMOUNE, R., SALVIA, M., MATHIA, T.G., BERTHEL, B., FOUVRY, S. and MESRATI, N. Effect of sandblasting substrate treatment on single lap shear strength of adhesively bonded PEEK and its composites. In: *Proceedings of ICCM-18*. Jeju Island, Korea, 21- 26 August 2011.

104. HELLMANN, H. and KRIEGER, R. US4906497 A - Microwave-activatable hot-melt adhesive. US4906497 A. 6 March 1990.

105. GANESAN, K., KARTHIK, R. and CHONGCHEN, X. Development and characterization of an all-olefin thermoplastic sandwich composite system. *Polymer Composites*. August 2002. Vol. 23, no. 4, p. 647–657.

106. TENCATE. *Aerospace composites - Product outline aerospace interiores - Tencate Cetex®System3®*. Tencate. [online] [Accessed 17 September 2014]. Available from: https://www.yumpu.com/en/document/view/22030220/tencate-cetex-system3-epicos/3

107. BIRON, M. *Thermoplastics and thermoplastic composites*. Amsterdam: Elevisier, 2012.

108. GREWLL, D and BENATAR, A. Welding of Plastics: Fundamentals and New Developments. *International Polymer Processing*. 2007. Vol. 22, p. 43–60.

109. GRIMM, R.A. Welding process for plastics. *Advanced Materials and Processes*. February 1995. Vol. 147, p. 27–30.

110. STOKES, V.K. Joining methods for plastics and plastic composites: an overview. *Polymer Engineering and Science*. 09/89. Vol. 29, p. 1310–1324.

111. BEEVERS, A. Welding: the way ahead for thermoplastics? *Engineering*. 1991. Vol. 231, p. 11–12.

112. WOOL, R.P. Welding of Polymer Interfaces. *Polymer Engineering and Science*. October 1989. Vol. 29, no. 19, p. 1340–1367.

113. YOUNG, H. K. and WOOL, R.P. A theory of healing at a Polymer-Polymer Interface. *Macromolecules*. 1983. Vol. 16, p. 1115–1120.

114. DIXON, J. *Packaging materials: 9. Multilayer packaging for food and beverages*. July 2011. ILSI Europe report series. International Life Science Institute. ISBN 9789078637264

115. BROCKHOLM JUHL, T. and BACH, D. Predicting the laser weldability of dissimiliar polymers. *Polymer*. 2013. Vol. 54, p. 3891–3897.

116. JABBARI, E. and PEPPAS, N. A. A model for interdiffusion at interfaces of polymers with dissimilar physical properties. *Polymer*. 1995. Vol. 36, no. 3, p. 575–586.

117. MARTINEZ, J.M, EGUIAZABAL, J.I. and NAZABAL, J. Miscibility of poly(ether imide) and poly(ethylen terephtalate). *Journal of Applied Polymer Science*. 1993. Vol. 48, no. 5, p. 935–937.

118. KARLSSON, K. F. and ASTRÖM, B. T. Manufacturing and applications of structural sandwich components. *Composites Part A*. 1997. Vol. 28, no. 2, p. 97–111.

119. TRENDE, A., ASTRÖM, B.T., WÖGINGER, A., MAYER, C. and NEITZEL, M. Modelling of heat transfer in thermoplastic composite manufacturing: double-belt press lamination. *Composites: Part A*. 1999. Vol. 30, p. 935--943.

120. SCHMACHTENBERG,E. and STROHHÄCKER, J. Thermoplastische Sandwichpaneele herstellen, verarbeiten und recyceln. *Plastverarbeiter 56. Jahrg.* 2005. Vol. Nr. 7, p. 34–35.

121. ISOSPORT-VERBUNDTEILE GMBH. WO9712756A1 - Composite panels and process for manufacturing them. WO9712756A1. 10 April 1995.

122. GIEHL, S. and MITSCHANG, P. Faserverstärkte Sandwich- und Profilstrukturen in einem Schritt. *Kunststoffe 11/2005*. November 2005. P. 76–78.

123. ROCH, A. and HUBER, T. Der Spritzgießer kann auch Leichtbau. *Industrieanzeiger*. 2012. No. 24/2012.

124. SCHREIER, P., MÜHLBACHER, M., FARAFA, M., NEUMEYER, T. and ALTSTÄDT, V. Multi-Materialsysteme - Sandwich mit thermoplastischen Partikelschäumen. *Emobilty tec*. February 2016. Vol. 02/2016, p. 58–61.

125. BEUKERS, A. Cost effective composite plate & shell structures for transports by manufacturing technologies like in-situ foaming, thermoforming and pressforming continuous fiber reinforced thermoplastic sheets. In: BRANDT, J., HORNFELD, H. and NEITZEL, M. (eds.). *Advanced Materials and Structures from Research to Application, SAMPE European chapter*. Niederglatt, Switzerland 1992. P. 427–443.

126. DE GROOT, M. T. EP 0636463A1 - A method of producing a thermoplastic sandwich plate. EP 0636463A1. 2 January 1995.

127. BRAMBACH, J. A. EP0313171 - Sandwich material and the use thereof. EP0313171. 26 April1989.

128. DE GROOT, M. T. EP1874517 B1- Verfahren zur Herstellung einer Sandwichplatte und Sandwichplatte als solche. EP1874517 B1. 10 August 2011.

129. BEUKERS, A. Low cost production technique for sandwich structures. In: *Proceedings of the 1st core conference*. Zürich, Switzerland, 20 - 21 October 1988.

130. ROCH, A., MENRATH, A. and HUBER, T. Fiber-reinforced thermoplastics as sandwich construction. *Kunststoffe international*. October 2013. Vol. 10/2013, p. 119–124.

131. ROCH, A., HUBER, T., HENNING, F. and ELSNER, P. LFT-Foams - Lightweight potential for structural components through the use of ling-glass-fiber-reinforced thermoplastic foams. In: *Proceedings of Polymer Processing Society 29th Annual Meeting (PPS29)*. Nuernberg, Germany, 15 -19 July 2013.

132. HENNING, F. and KUCH, I. Thermoplastic sandwich-structures with high content of recycled material- an innovative one step technology. In: *Proceedings of the American Society for Composites - 15th Technical Conference*. Texas, USA 25 - 29 September 2000. p. 195–205.

133. SORRENTINO, L., AURILIA, M. and IANNACE, S. Effects of the thermoforming on the cell morphology of a thermoplastic core. In: *Proceedings of 17th International Conference of Composite Materials – ICCM 17*. Edinburgh, Scotland 27 - 31 July 2009.

134. DE GENNES, P.G. Reptation of a Polymer Chain in the Presence of Fixed Obstacles. *Journal of Chemical Physics*. 1971. Vol. 55, p. 572–579.

135. MÖLLER, F. and MAIER, M. Material models for the process simulation of thermoplastic sandwich forming. In: *Proceedings of 11th International Conference for Composite Materials- ICCM-11*. Gold Coast, Australia, 14 - 18 July 1997. p. 333–342.

136. MÖLLER, F. and MAIER, M. Material modelling for the simulation of the forming process of all-thermoplastic sandwich components. In: *Proceedings of 42nd International SAMPE Symposium*. Anaheim, USA, 04 - 08 May 1997.

137. Thermoplastic composites for aerospace. *IAPD Magazin*. May 2010.

138. CURCIC, T. *Synthese und Charakterisierung von amphipolaren Blockcopolymeren und Untersuchungen des Phasenverhaltens in Mischung mit Polypropylen*. [PhD Thesis]. Stuttgart; Germany: University of Stuttgart, 2012.

139. UTRACKI, L. A. and WILKIE, C. A. *Polymer blends handbook*. Second Edition. New York, Heidelberg, Dordrecht, London: Springer, 2014.

140. KRAUSE, S. Polymer-polymer miscibility. *Pure & Applied Chemie*. 1986. Vol. 58, no. 12, p. 1553–1560.

141. HANSEN, C. M. *The three-dimensional solubility parameters and solvent diffusion coefficent*. [PhD Thesis]. Kopenhagen, Denmark: Technical University of Denmark, 1967.

142. DEUTSCHES INSTITUT FÜR NORMUNG E. V. *DIN EN ISO 11339 - Adhesives – T-peel test for flexible-to-flexible bonded assemblies*. Berlin: Beuth Verlag GmbH, June 2010.

143. HANSEN, C. M. *Hansen solubilty paramters - A user's handbook*. Second edition. Boca Raton, London, New York: CRC Press, 2007.

144. HSIAO, B. and SAUER, B. Glass Transition, Crystallization, and Morphology Relationships in Miscible Poly (Aryl Ether Ketones) and Poly (Ether Imide) Blends. *Journal of Polymer Science Part B: Polymer Physics*. 1993. Vol. 31, p. 901–915.

145. ARZAK, A., EGUIAZABAL, J.I. and NAZABAL, J. Phase behaviour and mechanical properties of poly (ether ether ketone)- poly (ether sulfone) blends. *Journal of Materials Science*. 1991. Vol. 26, p. 5939–5944.

146. SGRECCIA, E., M. KHADHRAOUI, M. and DE BONIS, C. Mechanical properties of hybrid proton conducting polymer blends based on sulfonated polyetheretherketones. *Journal of Power Sources*. 2008. Vol. 178, p. 667–670.

147. AKHTAR, S. and WHITE, J.S. Characteristics of Binary and ternary Blends of Poly (P-Phenylene Sulfide) with Poly (Bis Phenol A) Sulfone and Polyetherimide. *Polymer Engineering and Science*. 1991. Vol. 31, no. 2.

148. LAI, M. and LIU, J. Thermal and Dynamic mechanical properties of PES/PPS blends. *Journal of Thermal Analysis and Calometry*. 2004. Vol. 77, p. 935–945.

149. NARA, S. and OYMA, H. T. Effects of partial miscibility on the structure and properties of novel high performance blends composed of poly(8p-phenylen sulfide) and poly (phenylsulfone). *Polymer Journal*. 2014. Vol. 46, p. 568–575.

150. STANILAND, P.A. Poly(ether ketone)s. In: ALLEN, G. (ed) *Comprehensive Polymer Science and Supplements*. Oxford: Pergamon Press, 1989. pp. 483–497.

151. DOMININGHAUS, H., ELSNER, P., EYERER, P. and HIRTH, T. *Die Kunststoffe und ihre Eigenschaften*. 6th Edition. Berlin: Springer, 2005.

152. SCHWITALLA, A., SPINTING, T., KALLAGE, I. and MÜLLER, W.-D. Polyetheretherketon (PEEK) - ein vielversprechender Werkstoff für die Zukunft. *Umwelt-Medizin-Gesellschaft*. April 2014. Vol. 27, p. 255–261.

153. PORCHER INDUSTRIES. *Pi preg® for thermoplastic composites* [online]. [Accessed 4 July 2016]. Available from: http://www.porcher-ind.com/en/activity/composites-thermoplastic-composites-pipreg-_2_3_10.html

154. TOHO TENAX EUROPA GMBH. *Product Data Sheet Tenax®- E TPCL PEEK-HTA 40*. [online]. 12 October 2012. [Accessed 4 July 2016]. Available from: http://www.tohotenax.com/fileadmin/PDF/Datenbl%C3%A4tter_en/PDS_Tenax-E_TPCL-PEEK-HTA40_v10_2015-07-24_en.pdf

155. TOHO TENAX EUROPA GMBH. *Product data sheet Tenax® -E TPUD PEEK -HTS45* [online]. 19 February 2015. [Accessed 4 July 2016]. Available from: http://www.tohotenax.com/fileadmin/PDF/Datenbl%C3%A4tter_en/PDS_Tenax-E_TPUD_PEEK-HTS45_v09_2015-02-19_en.pdf

156. TIEKE, B. *Makromolekulare Chemie: Eine Einführung*. 3. Auflage. Weinheim: Wiley-VCH, 2014.

157. GE ENGINEERING PLASTICS. *Ultem® PEI Resin - Product Guide*.[online] June 2003. [Accessed 20 June 2016] Available from: http://www.hycompinc.com/PDFs/ULTEMProductBrochure.pdf

158. CREVECOEUR, G. and GROENINCKX, G. Binary blends of poly(ether ether ketone) and poly (ether imide): miscibility, crystallization behaviour and semicrystalline morphology. *Macromolecules*. 1991. Vol. 24, no. 5, p. 1190–1195.

159. HARRIS, J.E and ROBESON, L.M. Miscible blends of Poly(aryl Ether Ketone)s and Polyetherimides. *Journal of Applied Polymer Science*. 1988. Vol. 35, p. 1877–1891.

160. HAANAPPEL, S. *Forming of UD fibre reinforced thermoplastic - a critical evaluation of intra-ply -shear*. [PhD Thesis]. Twente, Netherlands: University of Twente, 2013.

161. YE, L., LU, M. and MAI, Y.-W. Thermal de-consolidation of thermoplastic matrix composites - I Growth of voids. *Composites Science and Technology*. 2002. Vol. 62, p. 2121–2130.

162. YE, L., CHEN, Z.-R., LU, M. and HOU, M. De-consolidation and re-consolidation in CF/PPS thermoplastic matrix composites. *Composites Part A*. 2005. Vol. 36, p. 915–922.

163. WOLFRATH, J., MICHAUD, V. and MANSON, J. -A.E. Deconsolidation in glass mat thermoplastic composites: Analysis of the mechanism. *Composites Part A*. 2005. Vol. 36, p. 1608–1616

164. XIAO, XR. A model for deconsolidation phenomenon in induction heating of thermoplastic resin composites. In: *Proceedings of 9th International Conference on Composite*. Madrid Spain, 12 – 16 July 1993.

165. HENNINGER, F., YE, L. and FRIEDICH, K. Deconsolidation behaviour of glass fibre-polyamide 12 composite sheet material during post processing. *Plastic, rubber and Composite and applications*. 1998. Vol. 27, p. 287–292.

166. WEIß, C., MÜNSTEDT, E and SANDNER, H. PEEK kleben. *Kunststoffe*. 2001. Vol. 91, no. 4, p. 98–101.

167. SMILEY, A.J., HALBRITTER, A., COGSWELL, F.N. and MEAKIN, P.J. Dual polymer bonding of thermoplastic composite structures. *Polymer engineering and Science*. April 1991. Vol. 31, no. No. 7.

168. BASTIEN, L. J. *Non-Isothermal Model for Fusion bonding of Thermoplastic Composites Using an Amorphous Film Technique - CCM Report 90-23*. October 1990. University of Delaware.

169. BASTIEN, L. J. and GILLESPIE, J. W. A Non-Isothermal Healing Model for Strength and Toughness and Fusion Bonded Joints of Amorphous Thermoplastics. *Polymer Science and Engineering*. December 1991. Vol. 31, no. 24, p. 1720–1730.

170. BUTLER, C. A, MCCULLOUGH, R.L., PITCHUMANI, R. and GILLESPIE, J. W. An analysis of mechanism governing fusion bonding of thermoplastic composites. *Journal of Thermoplastic Composite Materials*. July 1998. Vol. 11, p. 338–363.

171. YANG, F and PITCHUMANI, R. Healing of thermoplastic polymers at an Interface under Nonisothermal Conditions. *Macromolecules*. 2002. Vol. 35, p. 3213–3224.

172. WOOL, R.P. and O'CONNOR. A theory crack healing in polymers. *Journal of Applied Physics*. 1981. Vol. 52.

173. AGARVAL, V. *The role of molecular mobility in the consolidation and bonding of thermoplastic composite materials*. [PhD Thesis]. Delaware, USA: University of Delaware, 1991.

174. MANTELL, S.C. and SPRINGER, G. S. Manufacturing process models for thermoplastic composites. *Journal of Composite Materials*. 1992. Vol. 26, no. 16, p. 2348–2377.

175. DARA, P. H. and LOOS, A.C. *Thermoplastic Matrix Composite Processing Model - CCMS-85-10*. September 1985. Virginia Polytechnic Institute and State University.

176. LEE, W. and SPRINGER, G.S. A Model of the Manufacturing Process of Thermoplastic Matrix Composites. *Journal of Composite Materials*. November 1987. Vol. 21, p. 1017–1055.

177. PHILLIPS, R., SUNDERLAND, P., PHILIPPE, Berguerand and J.A., Manson. The effect of pressure gradients on the consolidation of fibre-reinforced thermoplastics. In: *Proceedings of 4th Int. Conf. on Flow Processes in Composite Materials (FPCM)*. Aberystwyth, Wales, 9 – 11 September 1996.

178. PHILIPS, R. *Consolidation and solidification behavior of thermoplastic composites*. [PhD Thesis]. Lausanne, Switzerland: EPFL, 1996.

179. YANG, F and PITCHUMANI, R. Nonisothermal Healing and Interlaminar Bond Strength Evolution During Thermoplastic Matrix Composites Processing. *Polymer Composites*. April 2003. Vol. 24, no. 2, p. 263–278.

180. STOKES-GRIFFIN, C.M and COMPSTON, P. Investigation of sub-melt temperature bonding of carbon-fibre/PEEK in an automated laser tape placement process. *Composites Part A*. 2016. Vol. 84, p. 17–25.

181. VEREIN DEUTSCHER INGENIEUR EVE. *VDI- Wärmeatlas*. 11. bearbeite und erweiterte Auflage. Heidelberg: Springer-Verlag, 2013.

182. GROUVE, W. *Weld-strength of laser-assisted tape-places thermoplastic composites*. [PhD Thesis]. Twente, Netherlands: University Twente, 2012.

183. MENGES, G., HABERSTROH, E., MICHAELI, W. and SCHMACHTENBERG, E. *Werkstoffkunde Kunststoffe*. 5. Auflage. München, Wien: Carl Hanser Verlag, 2002.

184. DEUTSCHES INSTITUT FÜR NORMUNG E.V. *DIN 53292 -Testing of sandwiches, tension test in flatwise plane*. Berlin: Beuth Verlag GmbH, February 1982.

185. DEUTSCHES INSTITUT FÜR NORMUNG E.V. *DIN EN ISO 10365 – Adhesives - Designation of main failure pattern*. Berlin: Beuth Verlag GmbH, August 1995.

186. DEUTSCHES INSTITUT FÜR NORMUNG EV. *DIN EN 2243-3 Luft- und Raumfahrt – Nichtmetallische Werkstoffe - Strukturelle Klebstoffsysteme - Prüfverfahren – Teil 3: Trommelschälversuch für Wabenkernverbunde. Berlin: Beuth Verlag GmbH,* October 2006.

187. DEUTSCHES INSTITUT FÜR NORMUNG E.V. *DIN 53294 - Testing of sandwiches, shear test in flatwise plane*. Berlin: Beuth Verlag GmbH, February 1982.

188. DEUTSCHES INSTITUT FÜR NORMUNG EV. *DIN EN 6061 Aerospace series – Fibre reinforced Plastics – Test Method -Determination of sandwich flexural strength-4 point bending*. Berlin: Beuth Verlag GmbH, April 1996.

189. ASTM INTERNATIONAL. *ASTM C 364/364M-16 Standard Test Method for Edgewise Compressive Strength of Sandwich Constructions*. West Conshohocken: ASTM International, April 2016.

190. DEUTSCHES INSTITUT FÜR NORMUNG E.V. *DIN 53291 - Testing of sandwiches, flatwise compression test*. Berlin: Beuth Verlag GmbH, February 1982.

191. AIRBUS INDUSTRIE. *AITM 1-0010- Airbus Industrie - Test Method - Fibre reinforced plastics - Determination of compression strength after impact*. Blagnac Cedex: Airbus Industrie, June 1999.

192. HUTCHINSON, J.W., MEAR, M.E. and RICE, J.R. Crack paralleling an interface between dissimiliar materials. *Journal of Applied Mechanics*. 1987. Vol. 54, p. 828–831.

193. DEGISCHER, H.P. and LÜFTL, S. *Leichtbau: Prinzipien, Werkstoffauswahl und Fertigungsvarianten*. Weinheim: Willey-VCH Verlag GmbH & Co. KGaA, 2009.

194. AVK - INDUSTRIEVEREINIGUNG VERSTÄRKTE KUNSTSTOFFE E.V. *Handbuch Faserverbundwerkstoffe: Grundlagen, Verarbeitung, Anwendungen*. 3rd Edition. Wiesbaden: Vieweg + Teubner, GWV Fachverlage GmbH, 2010.

195. KRUCKENBERG, T. and PATON, R. *Resin Transfer Moulding for Aerospace Structures*. Dordrecht: Springer Science + Business Media, B.V., 1998.

196. MARASCO, A.I., CARTIE, D.D.R., PARTRIDGE, I. K. and REZAI, A. Mechanical properties balance in novel Z-pinned sandwich panel: Out-of plane properties. *Composite Part A*. 2006. Vol. 37, p. 295–302.

197. ENDRES, G. *Beitrag zur Gestaltung, Auslegung und Optimierung von Kernverbunden für die Luftfahrtanwendung*. [PhD Thesis]. Stuttgart, Germany: University of Stuttgart, 2009.

198. ROBROEK, L. M. J. *The development of rubber forming as a rapid thermoforming technique for continuous fibre reinforced thermoplastic composites*. [PhD Thesis]. Delft, Netherlands: TU Delft, 1994.

199. HOU, M. and FRIEDRICH, K. 3-D stamp forming of thermoplastic matrix composites. *Applied Composite Materials*. March 1994. Vol. 1, no. 2, p. 135–153.

200. *Metals and Alloys – Densities* [online]. [Accessed 14 September 2016]. Available from: http://www.engineeringtoolbox.com/metal-alloys-densities-d_50.html

201. *Solids-Specific heat* [online]. [Accessed 14 September 2016]. Available from: http://www.engineeringtoolbox.com/specific-heat-solids-d_154.html

202. *Thermal Conductivity of some common Materials and Gases* [online]. [Accessed 14 September 2016]. Available from: http://www.engineeringtoolbox.com/thermal-conductivity-d_429.html

203. AGEORGES, C. and YE, L. *Fusion bonding of polymer composites*. London: Springer-Verlag London Ltd., 2002.

204. GAUGLER&LUTZ OHG. *Airex® R82 Materialdatenblatt DE 2011 V02* [online]. July 2011. [Accessed 4 July 2016]. Available from: http://www.gaugler-lutz.de/leicht-sandwichbau/airex-kernmaterial/airex-r82.html

12. APPENDIX

12.1 APPENDIX A

Table 25: Material data for heat transfer model

Press

Parameter	Symbol	Value	Unit	Source
Total height	h_p	0.08	m	
Node distance	dh_p	0.02	m	
Density	ρ_P	7850	Kg/m^3	[200]
Specific heat capacity	c_P	490	$J/(Kg\ K)$	[201]
Heat conductivity	λ_P	40	$W/(m\ K)$	[202]

Transfer plate

Parameter	Symbol	Value	Unit	Source
Total height	h_T	0.015	m	
Node distance	dh_T	0.015	m	
Density	ρ_T	2700	Kg/m^3	[200]
Specific heat capacity	c_T	450	$J/(Kg\ K)$	[201]
Heat conductivity	λ_T	200	$W/(m\ K)$	[202]

Skin/Laminate

Parameter	Symbol	Value	Unit	Source
Total height	h_L	0.002	m	
Node distance	dh_L	0.00066667	m	
Density	ρ_L	1540	Kg/m^3	[154]
Specific heat capacity	c_L	1300	$J/(Kg\ K)$	[203]
Heat conductivity	λ_L	0.71	$W/(m\ K)$	[203]

Core

Parameter	Symbol	Value	Unit	Source
Total height	h_C	0.020	m	
Node distance	dh_C	0.001	m	
Reduced node distance	$dh_{C,small}$	0.0001	m	
Density	ρ_C	110	Kg/m^3	
Density PEI-Melting	$\rho_{C,small}$	1300	Kg/m^3	[203]
Specific heat capacity	c_C	450	$J/(Kg\ K)$	measured
Specific heat capacity PEI-Melting	$c_{C,small}$	1250	$J/(Kg\ K)$	measured
Heat conductivity	λ_C	0.04	$W/(m\ K)$	[204]
Heat conductivity PEI-Melting	$\lambda_{C,small}$	0.22	$W/(m\ K)$	[203]

12.2 APPENDIX B

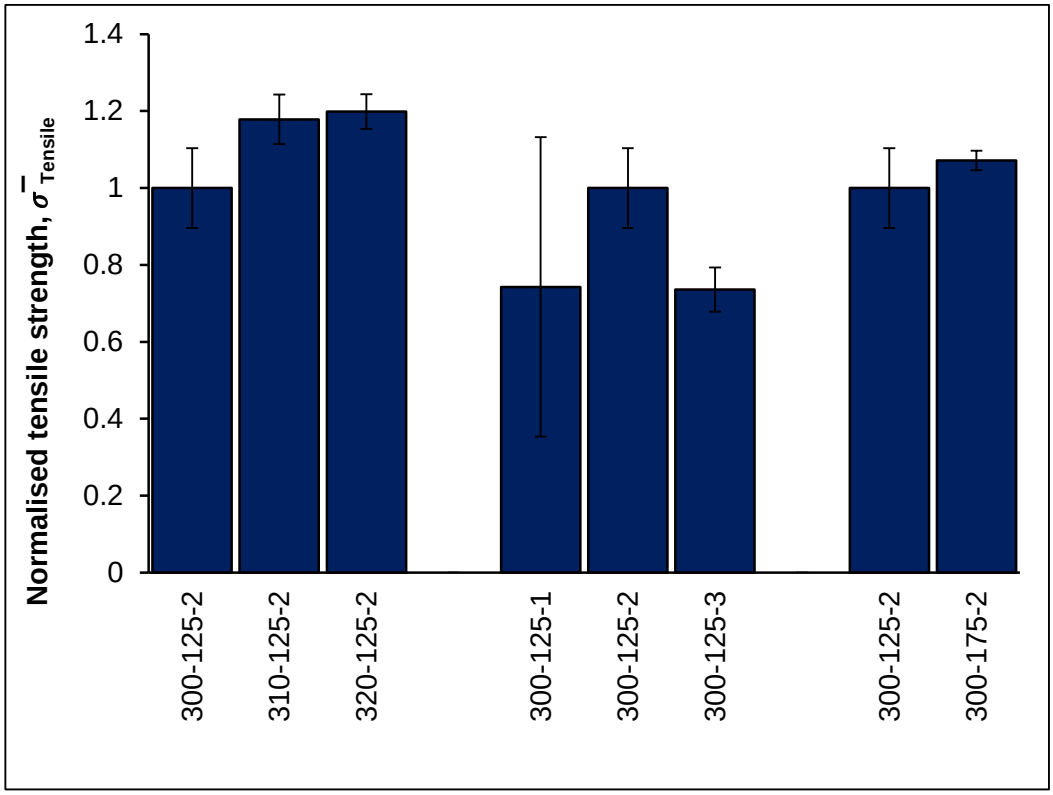


Figure 123: Normalised tensile strength results (normalised to 300-125-2)

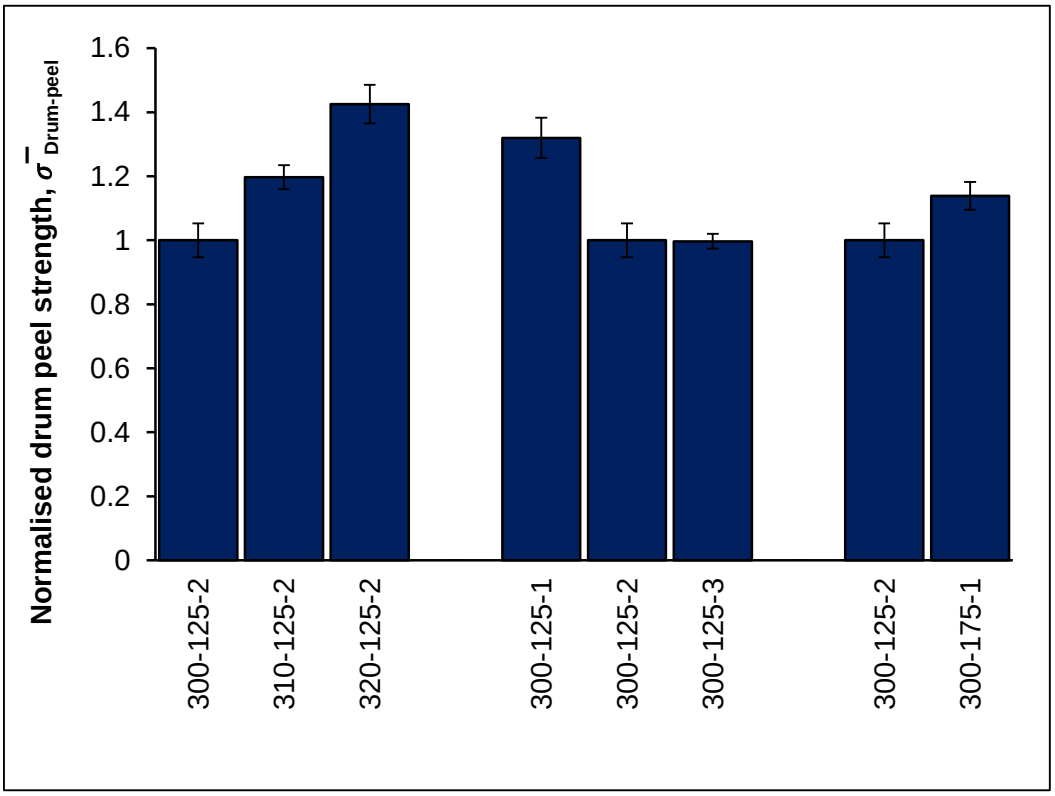


Figure 124: Normalised peel strength results (normalised to 300-125-2)

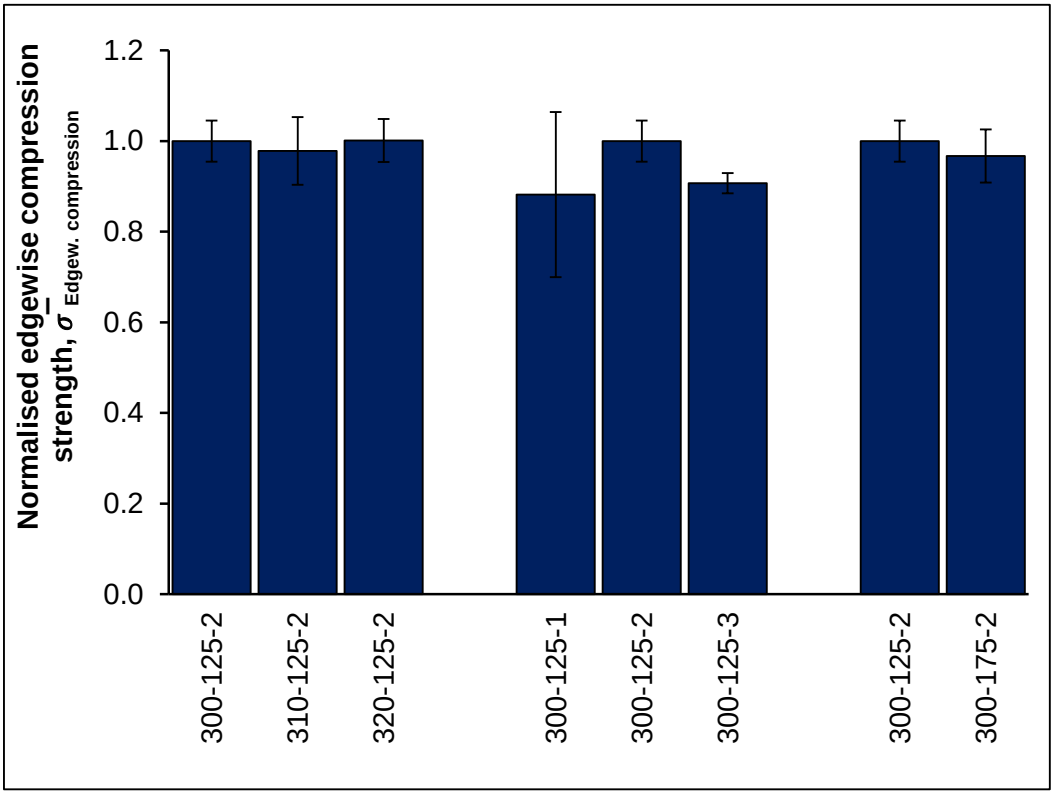


Figure 125: Normalised edgewise compression strength results (normalised to 300-125-2)

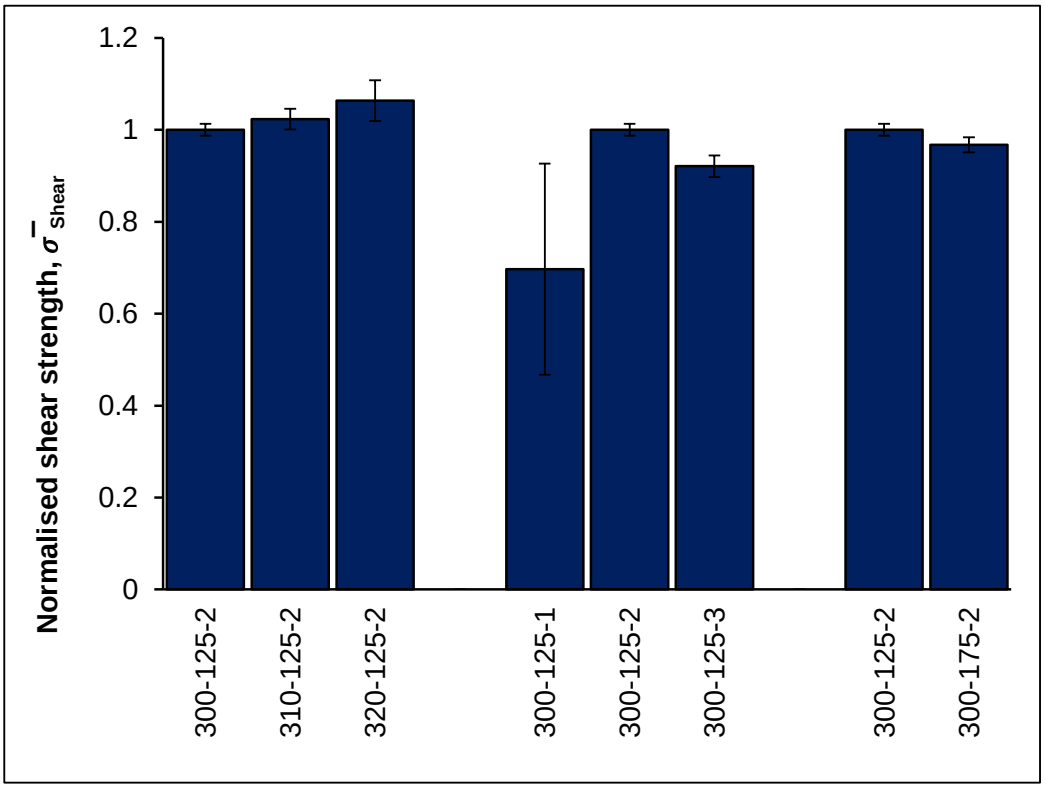


Figure 126: Normalised shear strength results (normalised to 300-125-2)

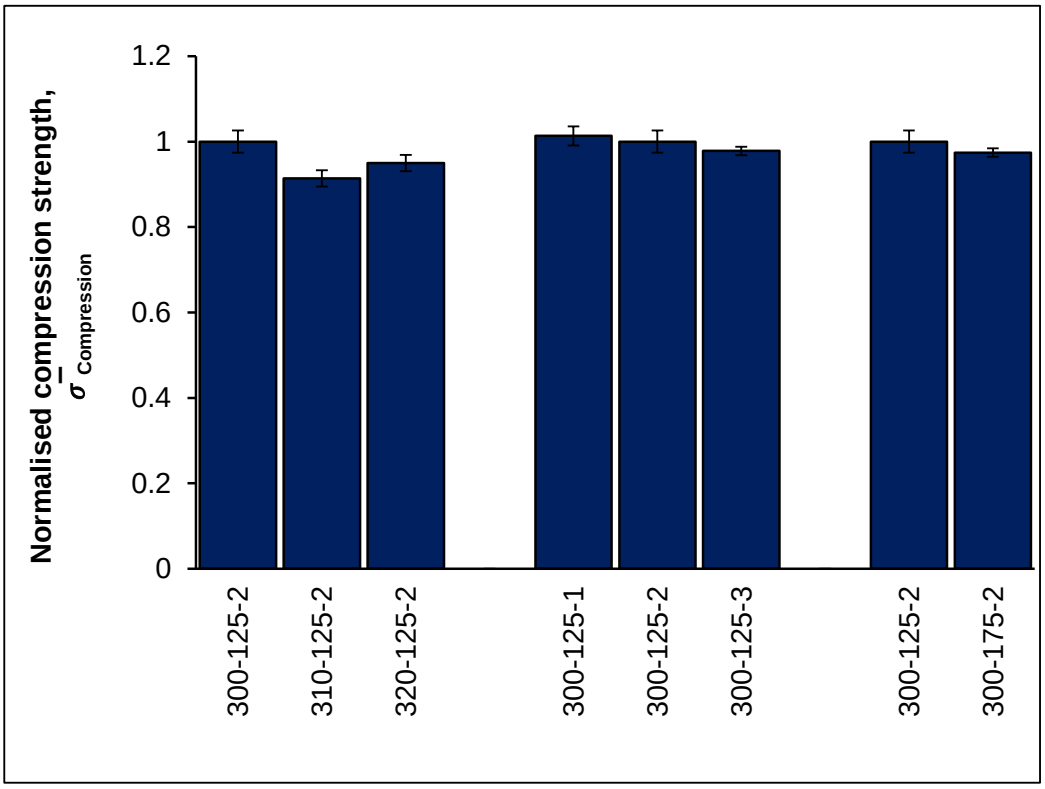


Figure 127: Normalised compression strength (normalised to 300-125-2)

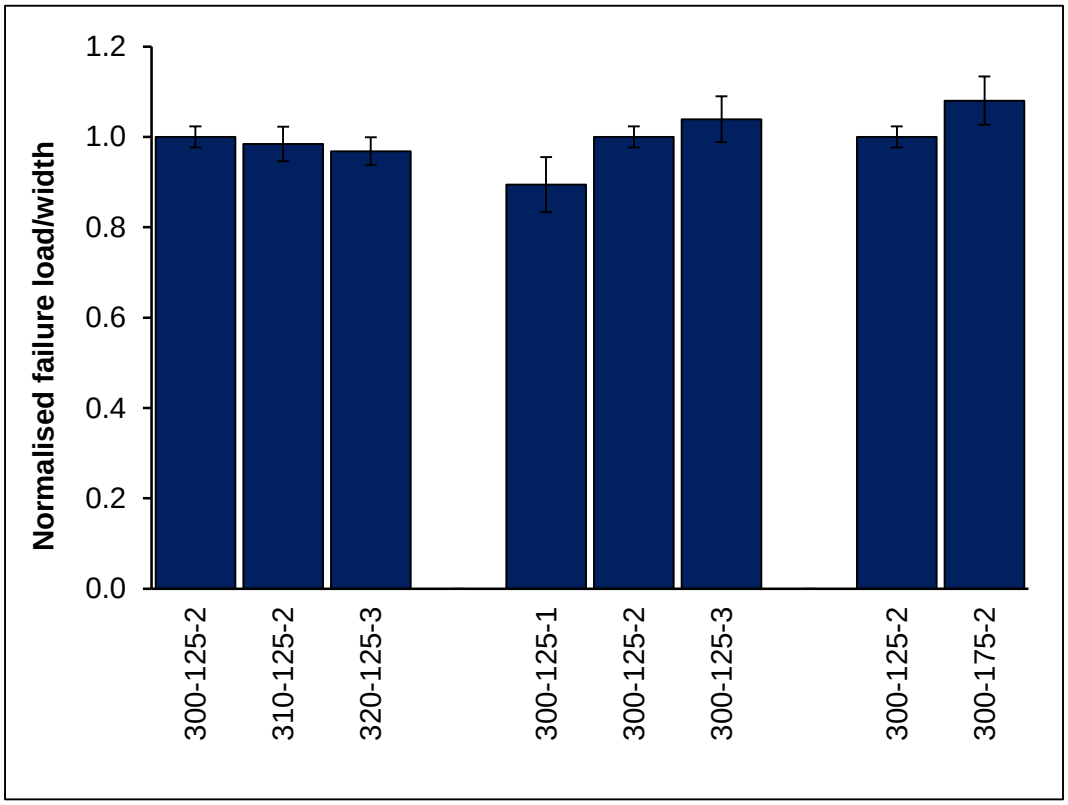


Figure 128: Normalised 4pt-bending results (normalised to 300-125-2)

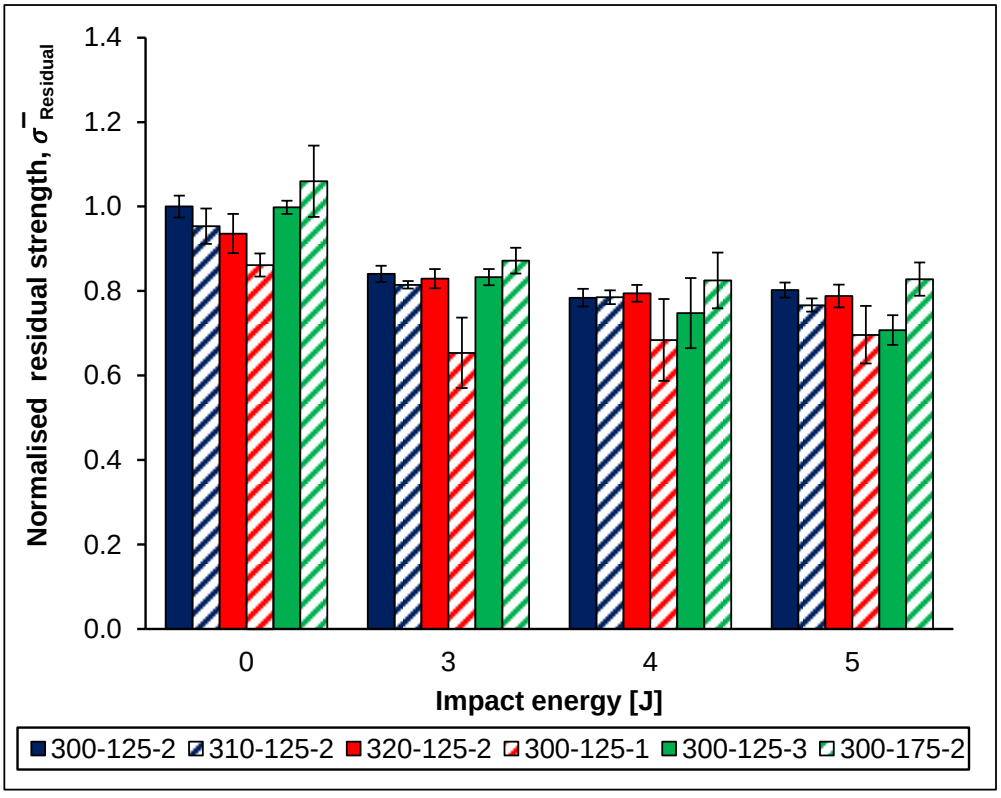


Figure 129: Normalized residual strength after impact (normalized to 300-125-2, 0J)

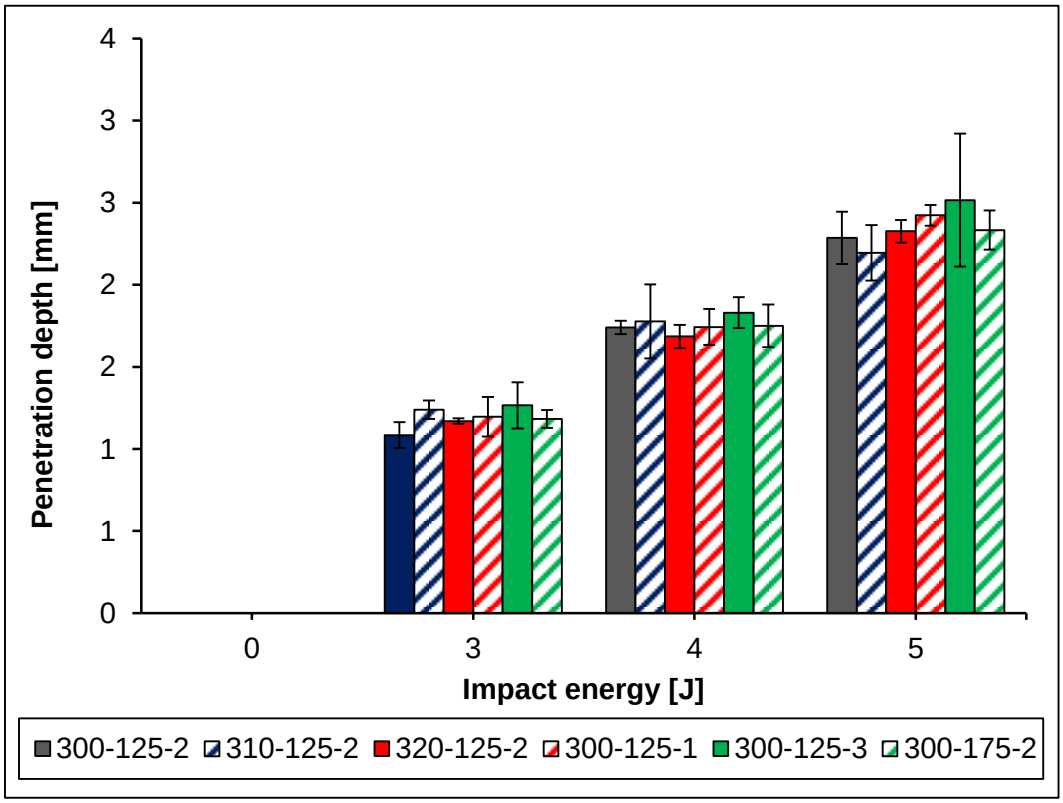


Figure 130: Penetration depth of impact weight

13. CURRICULUM VITAE

Personal	Jonas Grünewald born on 24.01.1988 in Cologne	
Family status	Single	
Nationality	German	
Education	2013 – 2018	Bayreuth University Bayreuth Degree: Dr. Ing
	2006 – 2012	RWTH Aachen, Aachen Degree: Diploma degree in mechanical engineering
	1998 – 2006	Geschwister-Scholl Gymnasium, Pulheim Degree: Abitur (High-School diploma)
	1994 – 1998	Elementary school, Pulheim
Profession/ Experiences	06.2017 – today	Toho Tenax Europe GmbH Position: Sales development manager
	04.2013 – 03.2017	Airbus Group Innovations, Ottobrunn Position: Research engineer
	06.2012 – 12.2012	Diploma Thesis at Eurocopter GmbH, Ottobrunn
	10.2011 – 03.2012	Internship at Volkswagen Group China, Peking
	2009 – 2011	Student research assistant at the Department for Textile Technology and Mechanical Engineering, RWTH Aachen, Aachen

14. PUBLICATIONS

Peer reviewed journals:

1)

Grünewald, J., Parlevliet, P.P., Altstädt, V.

Manufacturing of thermoplastic composite sandwich structures: a review of literature

Journal of thermoplastic Composite Material, Volume: 30 Issue: 4, Page(s): 437-464

Article first published online: September 24, 2015; Issue published: April 1, 2017

DOI: https://doi.org/10.1177/0892705715604681

2)

Grünewald, J., Parlevliet, P. P., Orth, T., Altstädt, V

Modified foam cores for full thermoplastic composite sandwich structures

Journal of Sandwich Structures and Materials, Article first published online: June 22, 2017

DOI: https://doi.org/10.1177/1099636217708741

3)

Grünewald, J., Parlevliet, P. P., Matschinski A., Altstädt, V.

Mechanical performance of CF/PEEK –PEI foam core sandwich structures

Journal of Sandwich Structures and Materials, Article first published online: July 31, 2017

DOI: https://doi.org/10.1177/1099636217715704

4)

Grünewald, J., Parlevliet, P. P., Altstädt, V.

Definition of process parameters for manufacturing of thermoplastic composite sandwiches – Part A: Modelling

Journal of Thermoplastic Composite Materials, Article first published online: September 11, 2017; DOI: https://doi.org/10.1177/0892705717722189

5)

Grünewald, J., Parlevliet, P. P., Altstädt, V.

Definition of process parameters for manufacturing of thermoplastic composite sandwiches – Part B: Model Verification

Journal of Thermoplastic Composite Materials, Article first published online: September 11, 2017, DOI: https://doi.org/10.1177/0892705717722189

Conferences:

1)

Grünewald, J., Parlevliet, P. P., Weimer, C., Altstädt, V.

Thermoplastic composite (TPC) sandwich structures for aeronautical applications

Sampe Europe, Amiens, France 15th-17th of September 2015

Grünewald, J., Parlevliet, P. P., Filsinger, J., Altstädt, V.

2)

Investigations on various sandwich materials and processes with respect to aerospace applications

ECCM17 - 17th European Conference on Composite Materials,

Munich, Germany, 26th-30th of June 2016

3)

Grünewald, J., Parlevliet, P.P., Orth, T., Altstädt, V.

Modified thermoplastic foam cores for structural thermoplastic composite sandwich structures

ITHEC 2016, 3rd International Conference of Thermoplastic Composites,

Bremen, Germany, 11th-12th of October 2016

Invention disclosure

1)

Grünewald, J., Parlevliet, P.P.

“Sandwich component and method for producing a sandwich component”- DE102014007510 (A1) – 26th September 2015

2)

Grünewald, J., Parlevliet, P.P., Meer, T.

“Sandwich component and method for producing a sandwich component”- DE102014007511 (A1) – 26th September 2015

3)

Orth, T., Grünewald, J., Parlevliet, P.P.

„Verfahren zur Herstellung eines Sandwich-Paneels mit einem verstärkten Schaumstoffkern“ Europa - Patentanmeldung 16176980.7